Novel LSS/CMB non-Gaussianities from Instabilities & Entropy Generation During and After Inflation

⇄

Generate fully-correlated nonGaussian Websky-Ensembles for CMB/LSS probes

Dick Bond @ PennState 19 02 01

Bond+Braden+Frolov+Huang+Morrison+Stein

varieties of primordial nonG and how to search for them

Simons Modern Inflation group - b2fhms & Eva Silverstein+ & Dan Green+

Origin of the observed entropy in the Universe and SMpp/BSMpp particles

- ***coarse-grained coherent condensate breaks up into fine-grained fluctuations***
- ***particle creation = (instability => stretch and break via mode-mode coupling aka fluctuation generation)***
- ***episodic stretching (adiabatic) and breaking (non-adiabatic ⟹ nonG) during inflation & after***

nonlinear multi-field classical coupled system*. evolve using lattice simulations. via* ***pseudo-spectral code & symplectic defrost++ code*** *=> very high accuracy to unveil small nonlinear effects leading to nonG*

$3\zeta(x,t) = \int_{\text{field-path}} (dE+pdV)/(E+pV) = \text{Trace}\ \alpha^{I}{}_{j} + \int_{\text{field-path}} d\ln \rho_{Ec}/(1+w_c)$

during inflation **(beyond stochastic inflation.** ***nonlinear k-space burst structure)***

$\langle \Delta\mathcal{P}_{\phi^A\phi^A}(k) \,|\, \Delta V, \Delta m^2_{eff} \rangle$, $\langle \Delta\mathcal{P}_{\zeta\zeta}(k) \,|\, \Delta V(\phi,\chi)\ \text{controls} \rangle$ $\langle \Delta\langle \prod \zeta^N \rangle_{cc} \,|\, \Delta V\ \text{controls} \rangle$ *SBB89, SB90,91 B95,..*

& ***after inflation ends*** **(modulated heating.** ***marginalize ~50 e-folds of sub-LSS)***

$\langle \zeta_{NL} | \chi_{cg} + \chi \rangle_h$

dynamical system Kolmogorov-Sinai entropy cf. true Shannon entropy

nonG ~ "particle" production ~ Shannon entropy generation

$\Delta s_{\text{flucs,k}} = \text{Trace} \ln[C_{\phi^A\phi^B} C_{\Pi_A\Pi_B} - C_{\phi^A\Pi_B} C_{\Pi_A\phi^B}]/2 \approx \ln(n_{\text{flucs,k}} + 1/2)$ *cf.* old way $\sim \ln[\rho_{Ak}(t)/\hbar\omega_{Ak}(t)]$

adiabatic flucs encoded in the collective Phonons, fluctuations + condensate = ζ_k

$< \delta_J(\mathbf{x},\mathbf{t}) \,|\, \zeta > = \chi_{J\zeta}(\mathbf{xt} \,|\, \mathbf{x_i}) * \zeta(\mathbf{x_i})$, $\chi_{J\zeta}$ = linear transfer fn $\forall$ fields $\mathbf{J}$

varieties of primordial nonG and how to search for them

perturbative, nonG part correlated with dominant Gaussian part

see Planck 2015/2018 nonG for exhaustive study and current constraints - 2018 including T+Epol

local fnl* - current limit cf. fnl target < 1. & equilateral orthogonal

if uncorrelated quadratic nonG suppressed by at least ~ $\mathcal{E}^2$

$$\langle \zeta_{NL} | \chi_{cg} + \chi_{>h} \rangle \sim \beta(\chi_{>h})\, \chi_{cg} + f(\chi_{>h})\, \chi_{cg}^2 +$$

$$f_{NL}^{equiv} = f\, [\beta P_\chi / P_{\zeta,inf}]^2 \quad \& \; P_\chi / P_\zeta \lesssim \varepsilon$$

Planck2015 .... Planck2018 not yet
nonG 3-point-correlation-pattern measure
f_{nl}: 2.7 ± 5.8 local for Newton potential
=> f_{NL*} =0.44 ± 3.5 for phonons/3-curvature
-f_{nl}: 42.3 ± 75.2 equilateral
-25.3 ± 39.2 orthogonal

beyond Planck2015/2018 nonG: some nonG probes in Planck 2015/2018 Isotropy & Statistics. main result is no strong evidence, anomalies

outside horizon (very): via stochastic inflation - huge nonG from feedback via diffusion *sb90/91 semi-eternal*

k-localized nonG: wide open. role of instabilities during inflation to make k-localized zeta-bursts. could even make PBHs. chain together instabilities - oscillations in power and 3-point. silverstein and Planck

new silverstein etal approach. explore higher N-points ⇒ anomalous tails.

BBM numerical pseudo-spectral codes to correct stochastic inflation, all weakly nonlinear terms included. B2FHMS can ensemble-measure everything, N-pt, coherences!

nonG from heating: 1 cm comoving scale => to be in observable LSS/CMB bands need modulation, but that is natural if there are light fields (heavy fields damp power)

nonG in long-lived field-condensates: strings, oscillons, curvaton structures, … short-scale short-lived

nonG bubbles from tunneling during inflation bbm

nonG from later phase transition structures - need first order (discontinuity in entropy - latent heat) cf. second order (discontinuity in second derivative aka in fluctuations) or smoother higher order, eg adiabatic evolution of particle content - entropy conserving

nonG from out-of-equilibrium decays *Bond+Braden+Frolov+Huang+Morrison & Stein*

ζ TOPOGRAPHY & CARTOGRAPHY

of our Hubble-patch bit of the early universe: RECONSTRUCT

Beyond the Standard Model of cosmology? *SMc = tiltedΛCDM +r via (ζ,h+x)*

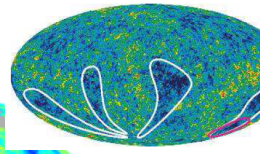
BSMc = SMc + primordial anomalies (nonG) in the true ζ -WebSky

anomalies @ low L => sample variance limited ~2σ's *CMB TT power L~ 20-30 dip => ζ-Spectrum k-dip*

$<\zeta\,|Temp,\ E\ pol> + \delta\zeta_{fluc}$

$d\zeta_c(x,t) = d\ln\rho_c / 3(1+w_c) + Trace(d\alpha_c)$

δs ~3 bits



ζ via Planck 2018 T,E map
@15 arcmin fwhm
≈ Planck 2015 XVII nonG

GUTA = Grand Unified Theory of Anomalies?

the rare cold spot
δs ~ 15 bits

>4.5σ
<1%
L~20
LSS
void?

-40.0 +40.0

BFH, b+frolov+huang

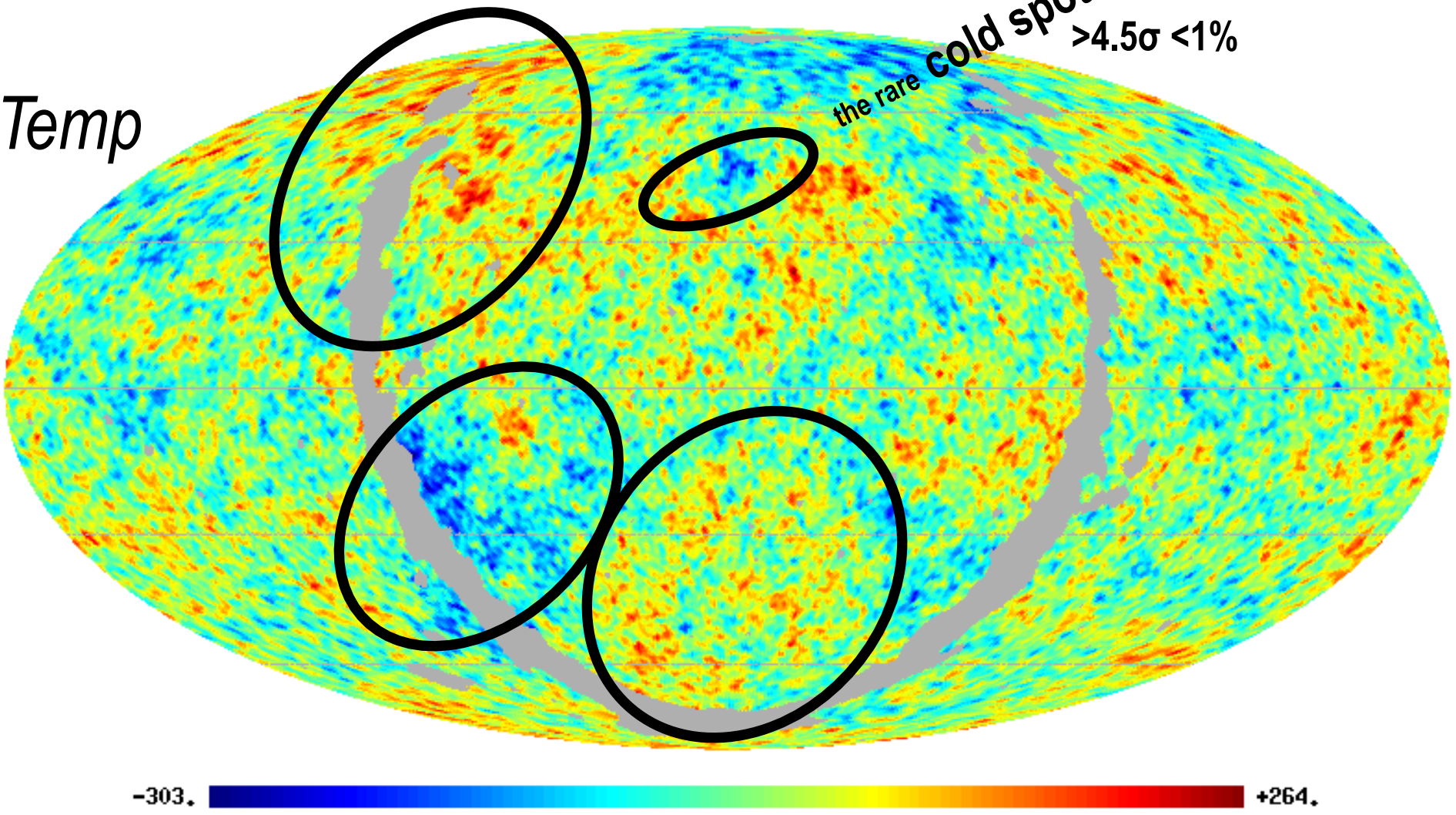
CMB ~*10,000,000 T/E modes of tΛCDM*
≲*500 modes of anomaly*
≲*100 modes reionization history*

CMB modes ~ $f_{sky} L_{max}^2$

LSS ⇒ *tomography* X k_{max} d_{max}

the rare **cold spot** >4.5σ <1%

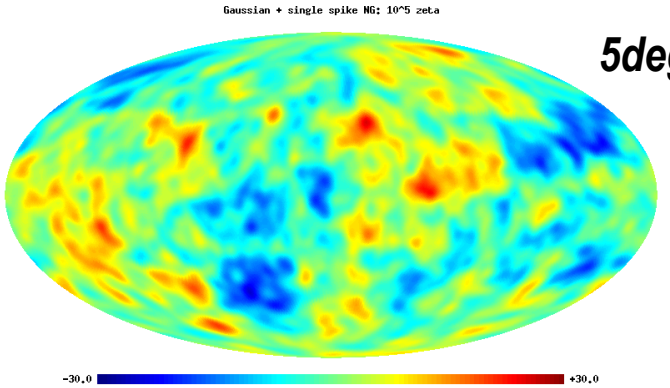
Temp



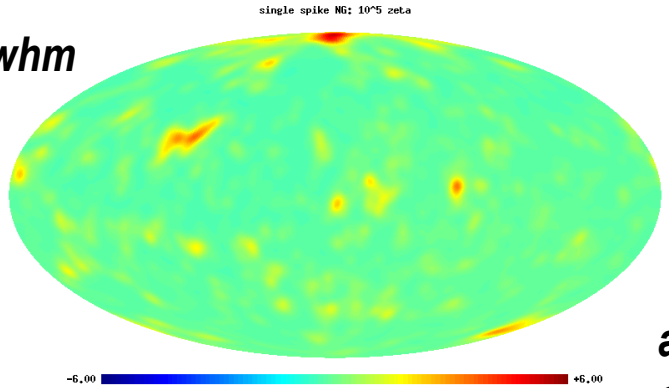
2D intermittency WMAP cold spot

CMB+LSS mocks to test: standard Gaussian inflaton ζ_{inf}+ subdominant uncorrelated ζ_{isoc}

e.g., ***from modulated preheating***



5deg fwhm



scan sims to get chance intermittent alignment to get a WMAP "cold spot"

intermittent nonG from early U preheating lattice sims

- here tunable peak model

also cf. quadratic nG:

correlated f_{NL}

uncorrelated large f_{NLeff}

uncorrelated nonG 'wide open' cf. usual correlated highly constrained nonG

the **true quadratic ζ-Websky** of the **ζ-scape**

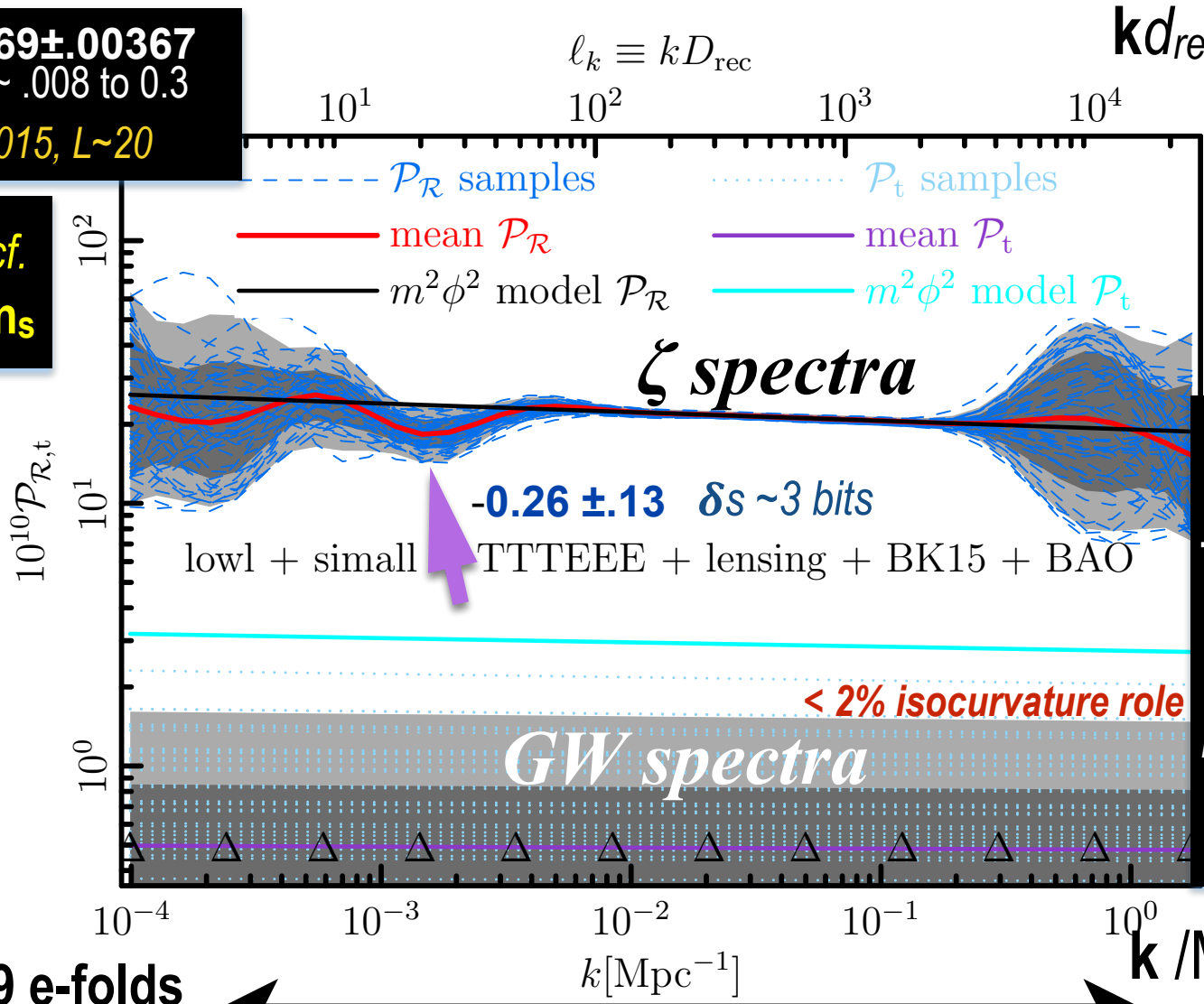
Planck 2018 X inflation: TTTEEE lowL Epol + CMBlens + BK15 BB + *BAO*

Anomalies in CMB TT power: L~ 20-30 dip => ζ-Spectrum k-dip ~2σ
includes CMB lensing, parameter marginalization

uniform n_s=0.9669±.00367
superb 12-knot fit k~ .008 to 0.3
δs ~3 bits @ k ~ .0015, L~20

r<.069 95%CL *cf.*
r<0.061 uniform n_s

stochastic inflation
$|\phi_{cg}\,;\,\phi_{fg}\rangle$
coherent state picture
of coarse-grain
condensate
+ *fine-grain*
bugoliubov fluctuations
QM-correct



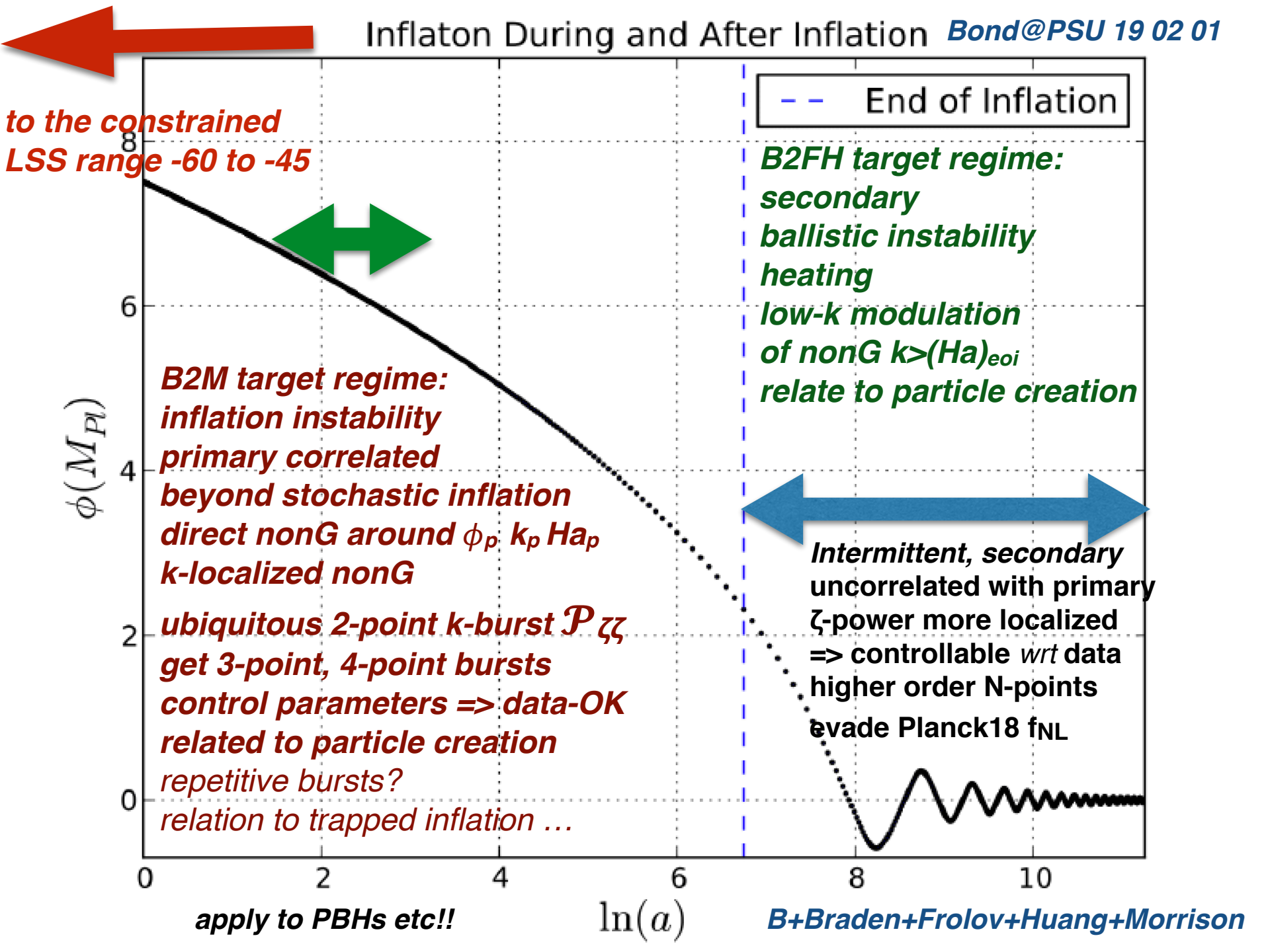
kd$_{rec}$ ≳L

derive
V(ϕ)
H(α)
ε(α)

=> lots of room for large N≥2pt ζ =>
k-localized nonG during inflation

9 e-folds

k /Mpc


Inflaton During and After Inflation
Bond@PSU 19 02 01
End of Inflation
to the constrained
LSS range -60 to -45
B2FH target regime:
secondary
ballistic instability
heating
low-k modulation
of nonG k>(Ha)eoi
relate to particle creation
B2M target regime:
inflation instability
primary correlated
beyond stochastic inflation
direct nonG around φp kp Hap
k-localized nonG
ubiquitous 2-point k-burst Pζζ
get 3-point, 4-point bursts
control parameters => data-OK
related to particle creation
repetitive bursts?
relation to trapped inflation …
Intermittent, secondary
uncorrelated with primary
ζ-power more localized
=> controllable wrt data
higher order N-points
evade Planck18 fNL
$\phi(M_{Pl})$
$\ln(a)$
0
2
4
6
8
10
apply to PBHs etc!!
B+Braden+Frolov+Huang+Morrison

Webskys: Mocking *with PeakPatches+Hydro+*

THEN BBKS, BCEK, B+Myers91,93,96, BKP96 web, BW96 importance

NOW: CITA mini-industry Alvarez, Bond, George Stein 2018, .. Validation SAB18 + Euclid 2018 validation a,b,c

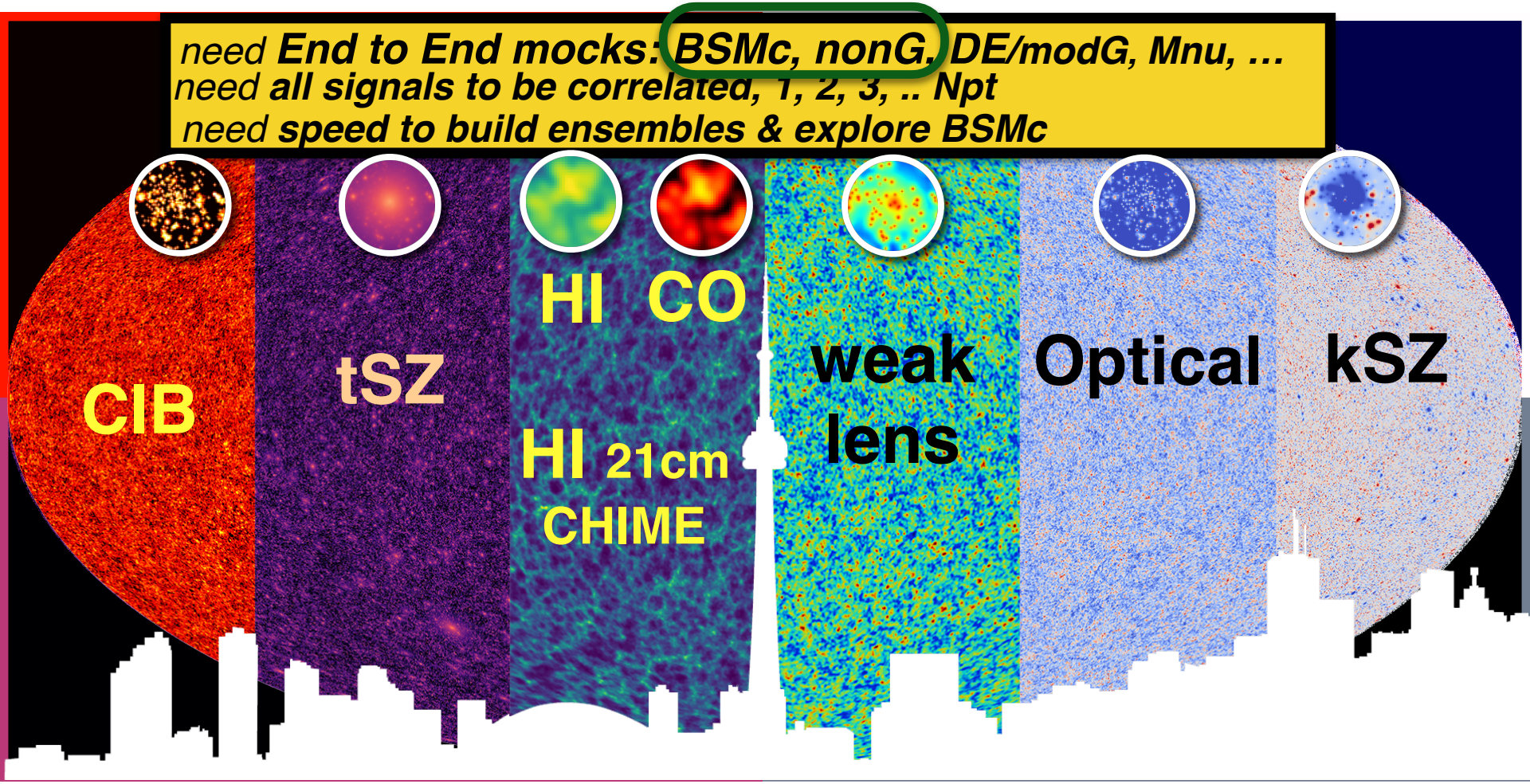
Berger, Battaglia, Codis, van Engelen, Motloch, Huang, Frolov,

now 19.2 Lague, Lokken, Murray, Keating, Lahklani, Breysse, bruno, connor, ronan, furen, remi, jason lee ++

*need **End to End mocks: BSMc, nonG, DE/modG, Mnu, …***

*need **all signals to be correlated, 1, 2, 3, .. Npt***

*need **speed to build ensembles & explore BSMc***



Planck, AdvACT, SO, CMB-S4, CCATp, EUCLID, LSST, DES, CHIME, HIRAX, COMAP, …SKA

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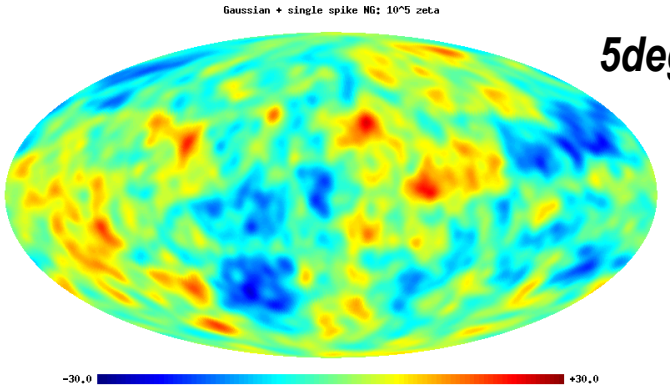
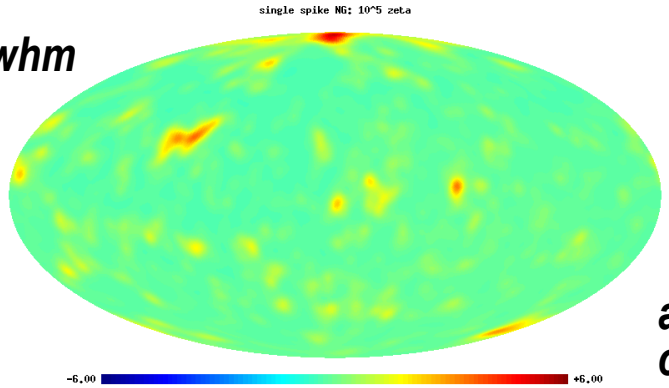
e.g., ***from modulated preheating***



5deg fwhm



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tunable peak model

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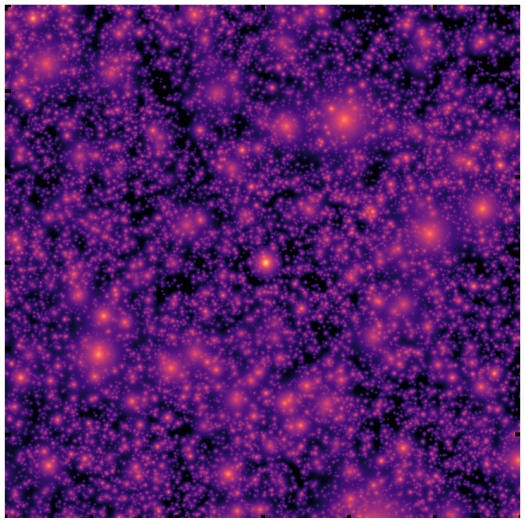
3D intermittency

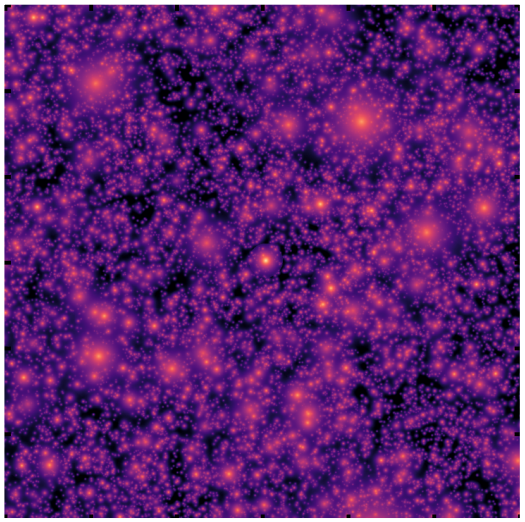
uncorrelated nonG 'wide open' cf. usual correlated highly constrained nonG

LSS tSZ: Gaussian std



B2FH, b+braden+frolov+huang

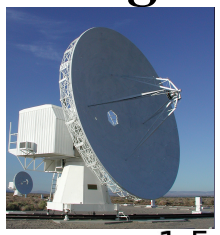
LSS tSZ: Gaussian std + subdominant uncorrelated ζ



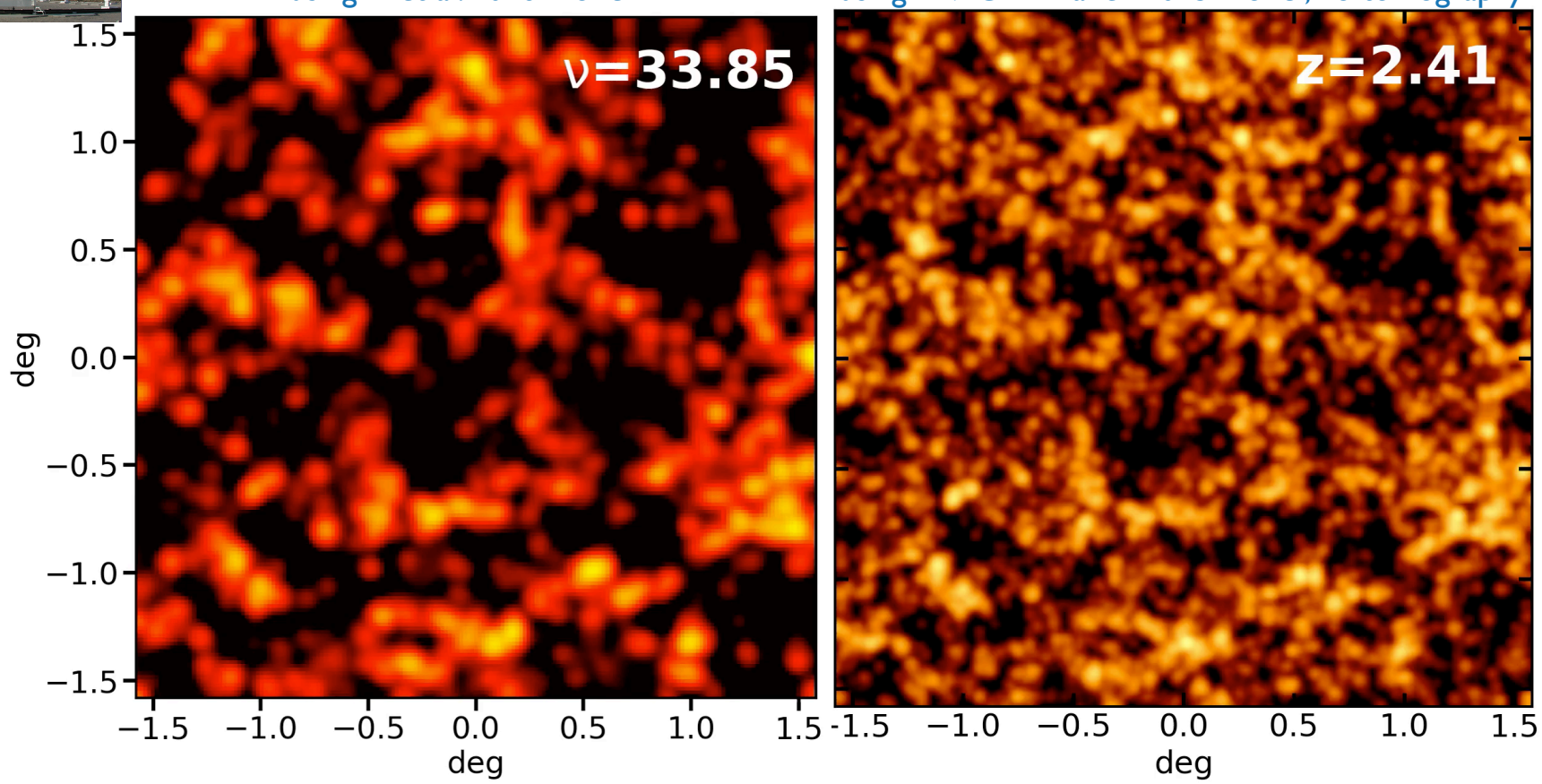
ABSB+FH, alvarez+b+stein+frolov+huang

COmap sims using Li+ Mhalo ⇒ L_{CO} *cf.* CIB *a la* Planck13,15

Danger: correlated stochasticity of bursty star formation etc.



z=2.4-3.4 eventually z=6-8 *cf. CHIME HI z=.8-2.5*



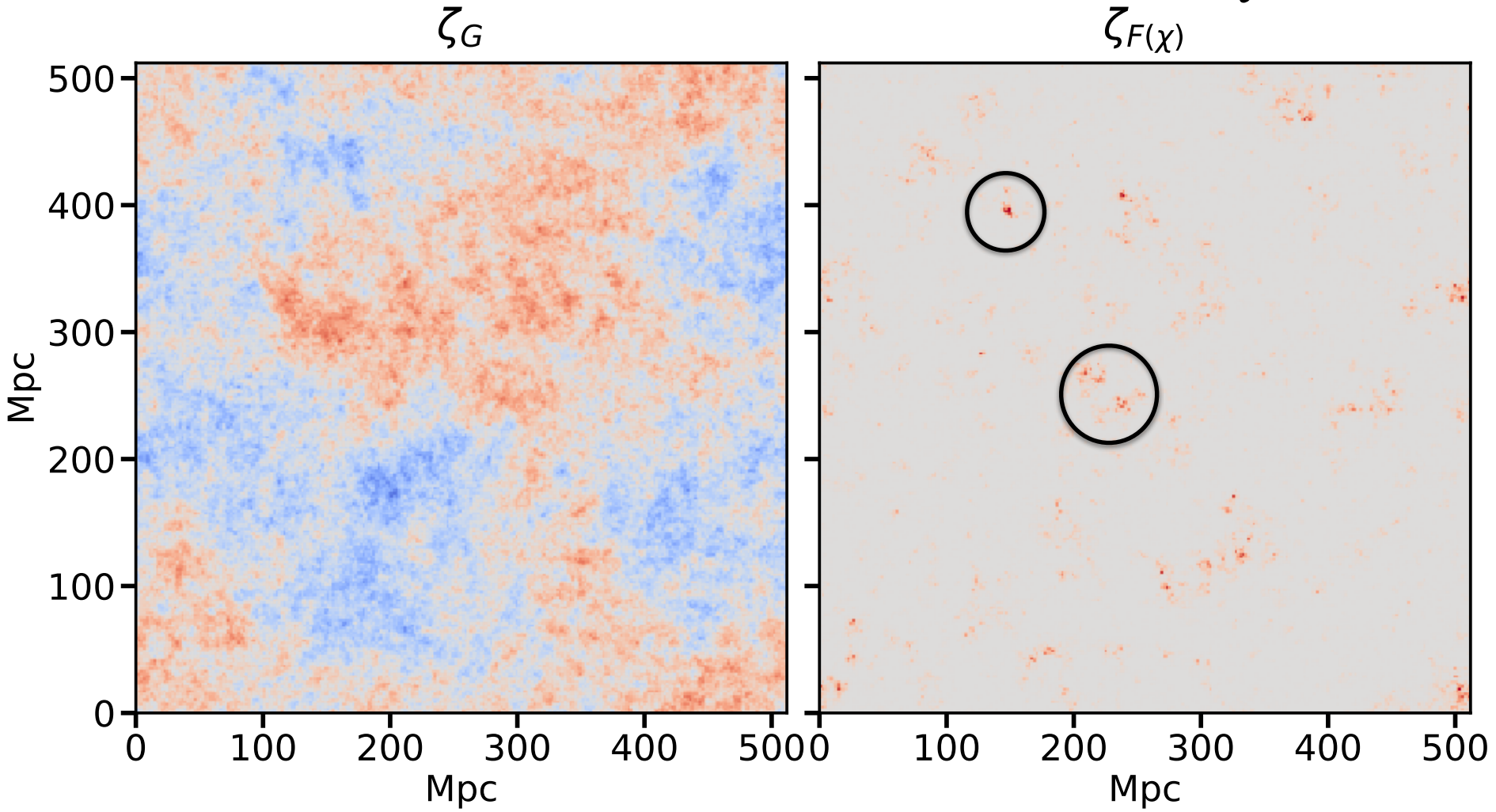
underway: **Lensing of CIB COmap HImaps kSZ tSZ**

nonG sources seen through a nonG lens

Primordial Non-Gaussianity in observable Webskys constructed with the mass-Peak Patch method
+ gas-halo response functions/susceptibilities

Intermittent Non-Gaussian case

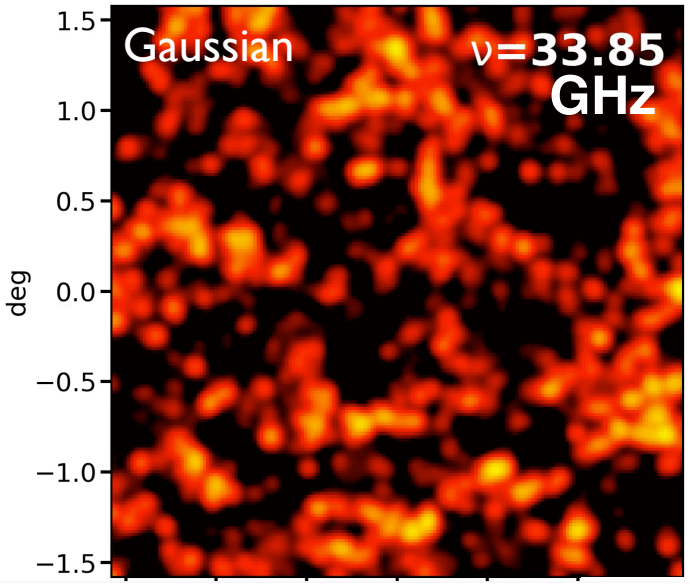
***uncorrelated* ζ[GRF]**

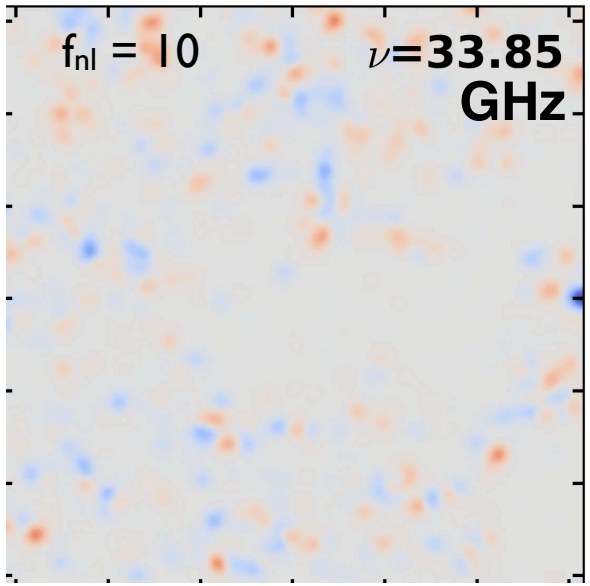


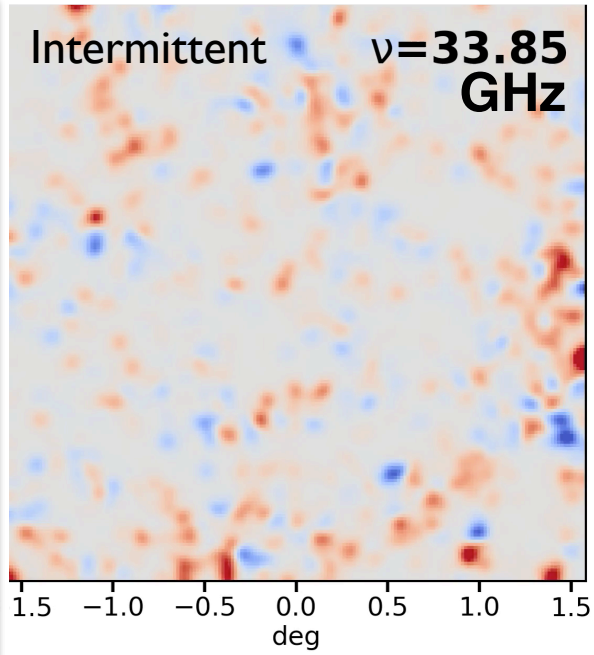
Bond , Huang, Stein; Braden, Morrison, …

Primordial Non-Gaussianity in CO example: the LCDM signal and 2 nonG difference maps - a movie

$\sigma_8 = 0.82$
In all cases

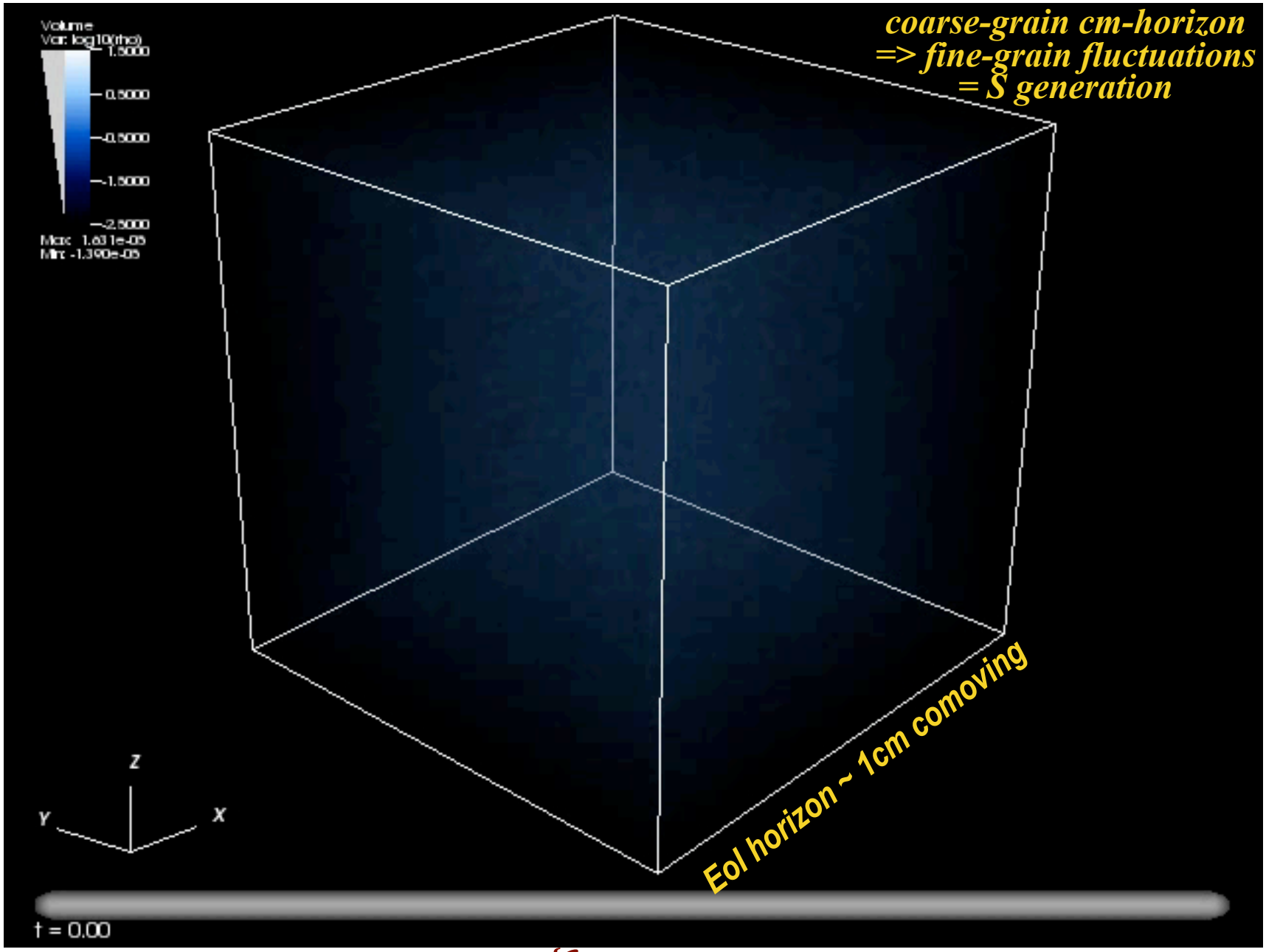






large scale => CHIME much larger volume is better

quartic inflaton $V(\phi,\chi) = 1/4\ \lambda\phi^4 + 1/2\ g^2\phi^2\chi^2$



log-normal pdf (density aka ζ), in k-bands too; normal pdf (velocity)

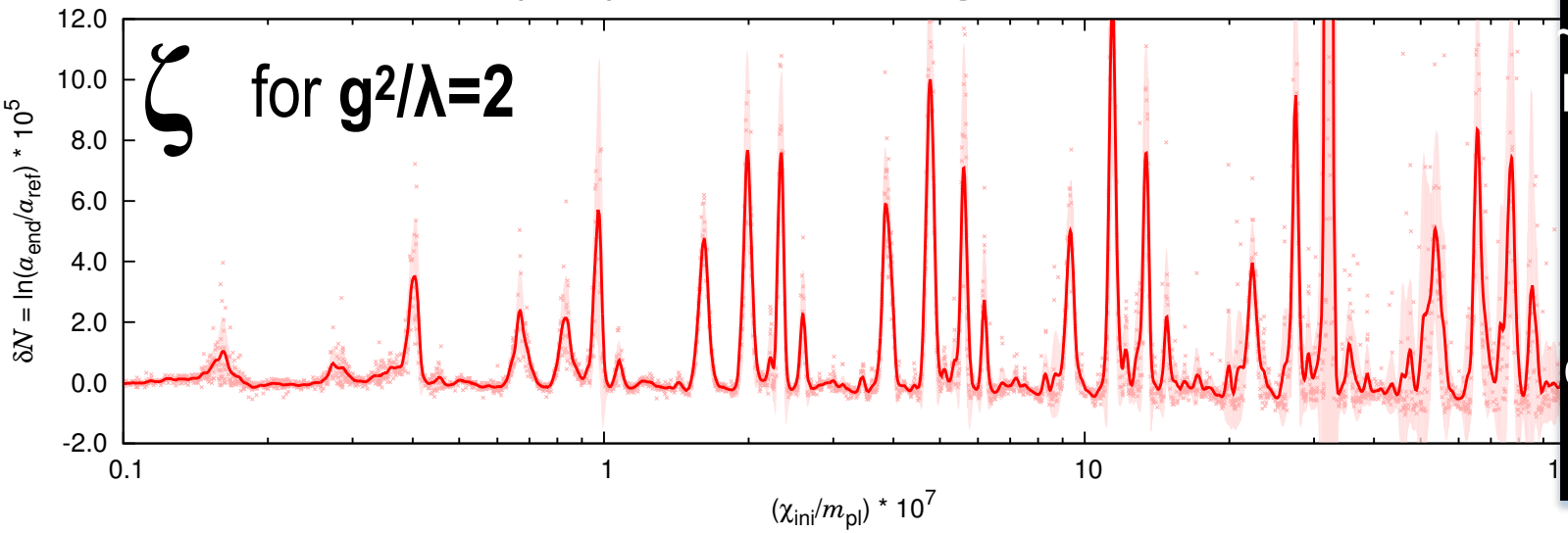
after inflation - instabilities => entropy => nonG

$dS/dt(t,g)$ => *the Shock-in-time: entropy production rate*

$\zeta_{shock}(\chi_{c,eoi}(x) \mid g^2/\lambda)$ => ***Chaotic Billiards: NonG from Parametric Resonance in Preheating***

B+Frolov, Huang, Kofman 09
B+Braden, Frolov, Huang 19

$$V(\phi,\chi)=1/4\ \lambda\phi^4+1/2\ g^2\phi^2\chi^2$$

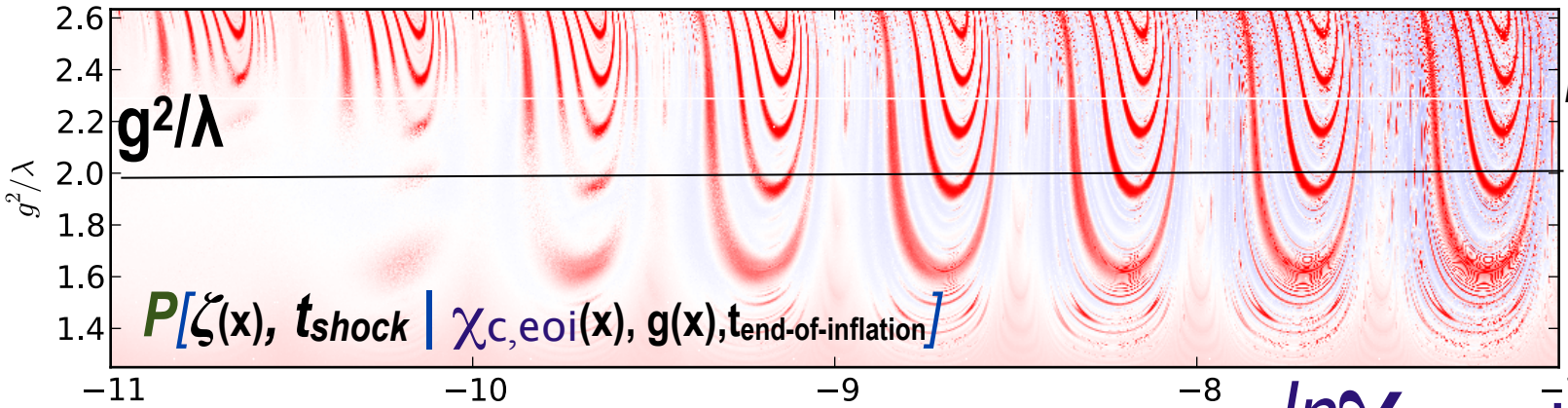


smooth **over** ~50 e-folds **of HF structure**

$\chi_c \Rightarrow \zeta_c$

ζ–bias cf. late-time density-bias

$\chi_{>h}$ control parameter



computational tour de force

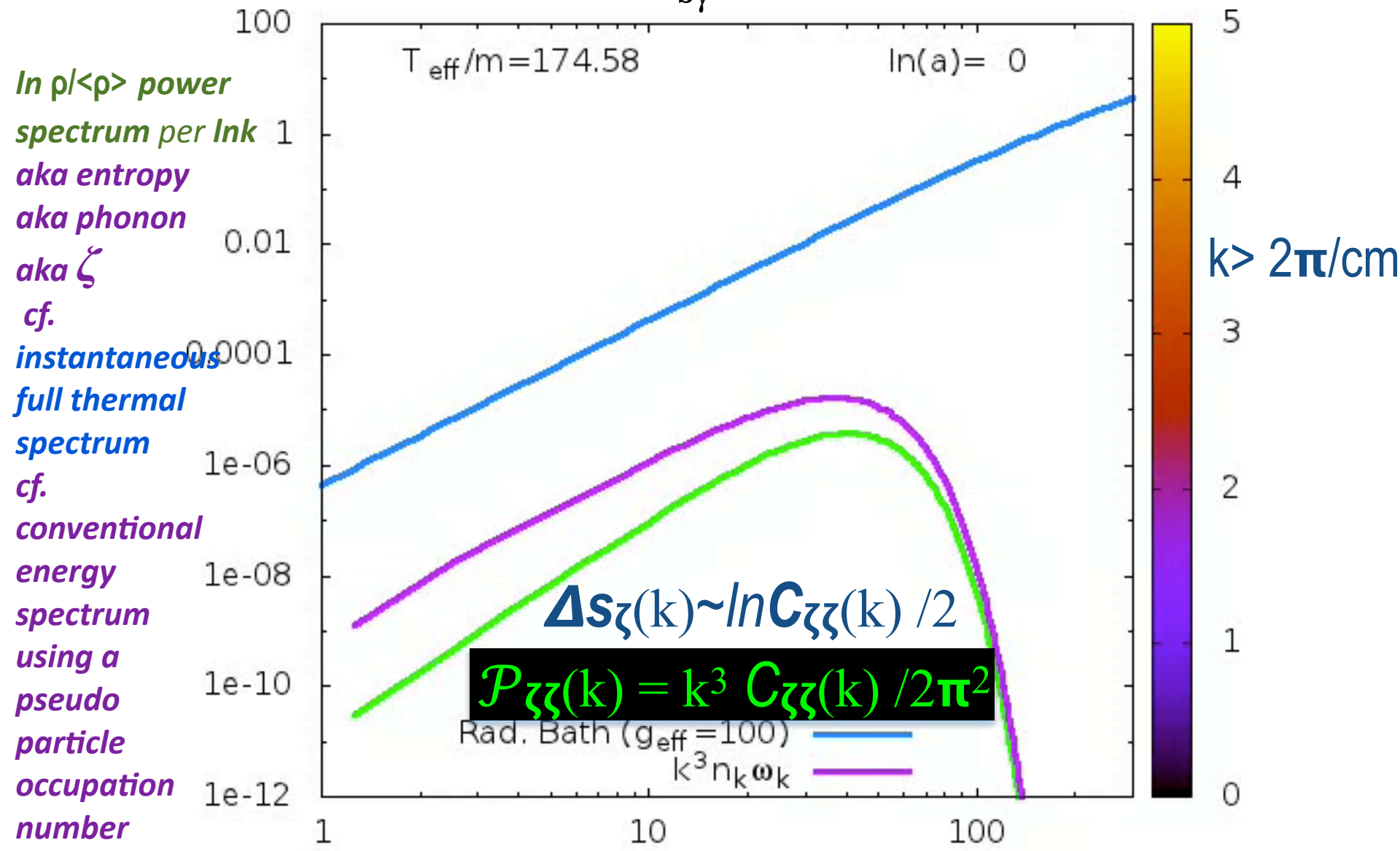
huge number of 64^3 ***sims to show the wondrous complexity of*** $\zeta(\chi_c, g^2/\lambda)$

gigafigure of ***lattice*** *simulations* $\ln(\chi_0/\phi_0)/\mu_0 T$

$ln\chi_{c,eoi}/M_{PL}$

coherent inflaton => incoherent mode cascade of fields thru a shock-in-time to thermal equilibrium

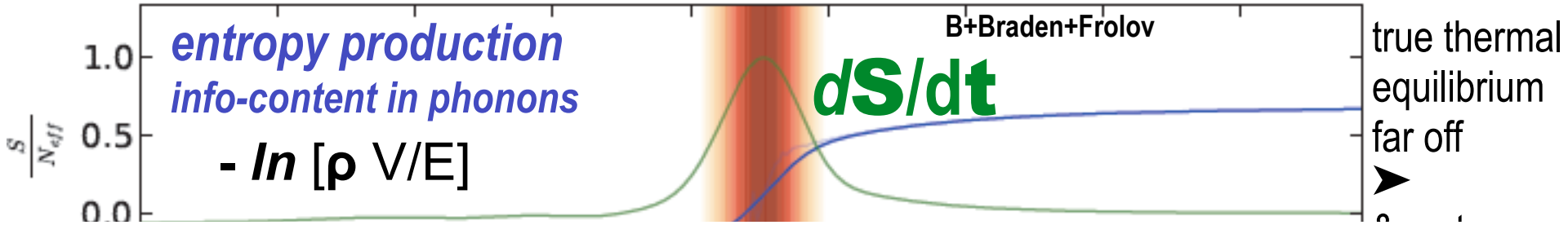
s_{Ui}~0; $s_{Utot,m+r}/n_b$ ~1.66x10^10 bits/b; s_γ/n_γ =5.2 bits/Υ =2130/411; s_v =21/22



V(ϕ,χ)=1/2 m2 ϕ2 +1/2 g2 ϕ2

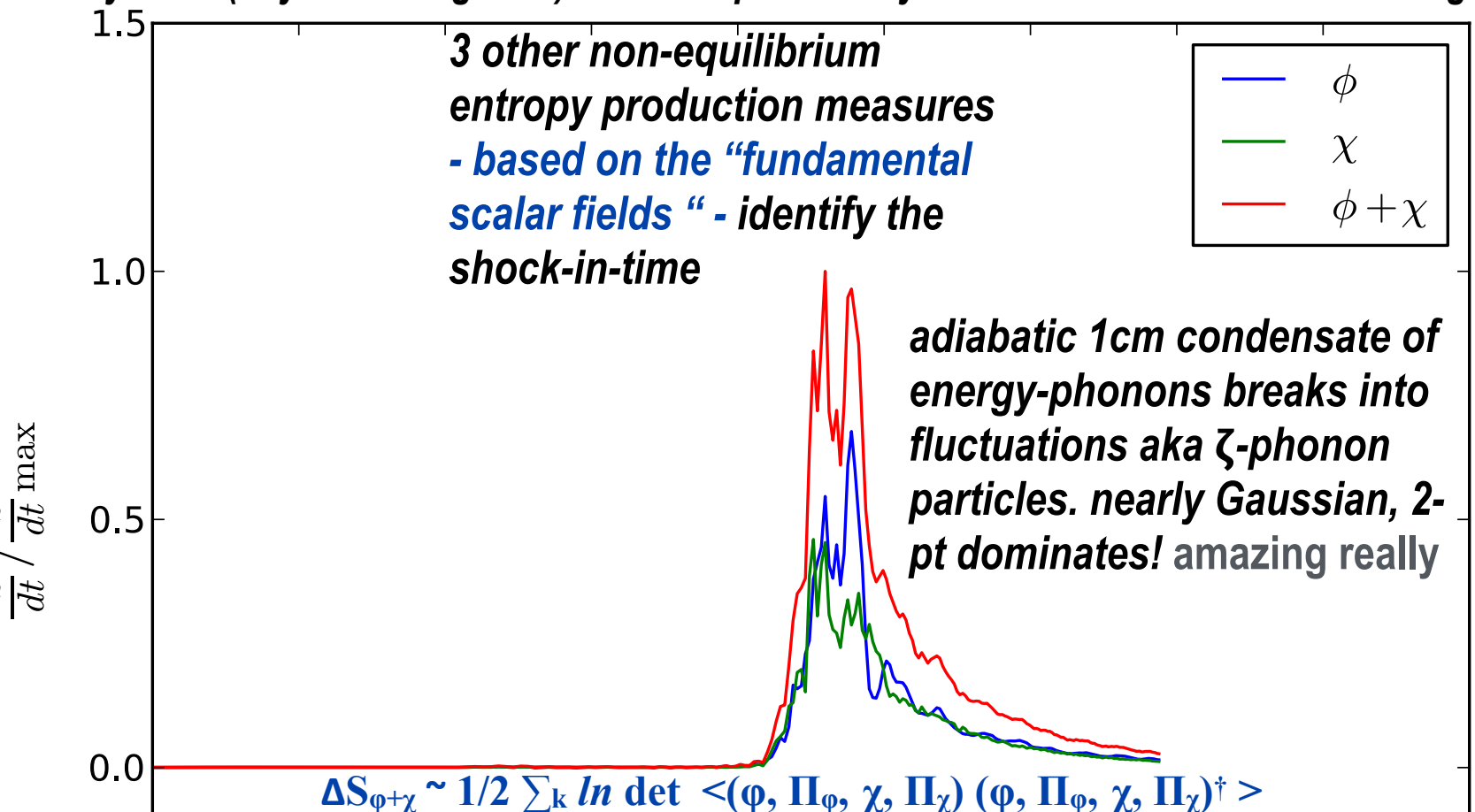
B+Braden+Frolov

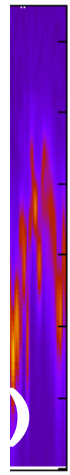
nonG from large-scale modulations of the shock-in-times of preheating



entangled primary fields $(\varphi, \Pi_\varphi, \chi, \Pi_\chi)$

decay rates (Feynman diagrams) and transport theory difficult to make accurate through preheating





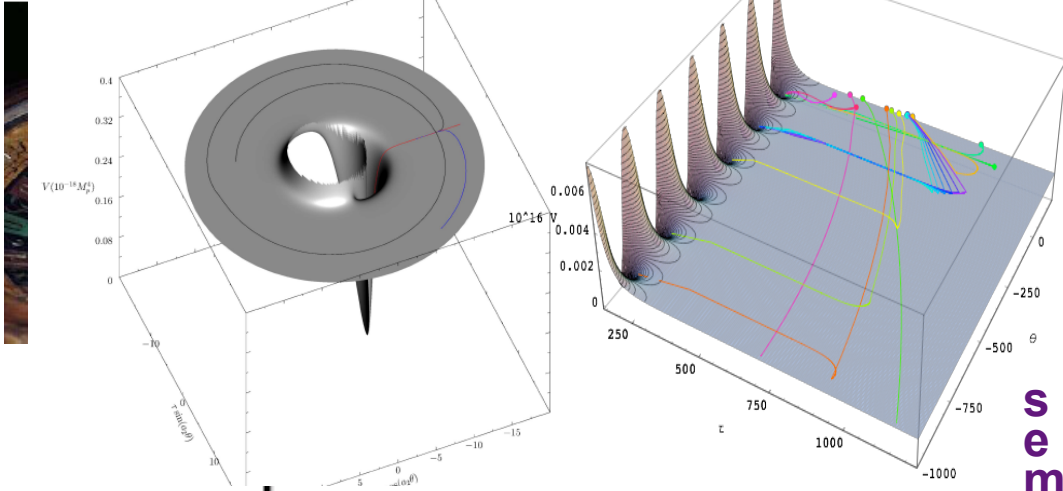
generic nature of ζ-spikes post inflation - lessons learned

<**ζ**| V-control **χ**-control g^2 -control,…>

multi-arm/filament potentials: here 4, but 3, 5-star,.. angular $V = \sum V_M(r) \cos(M\boldsymbol{\theta})$
modulate coupling "constants" in potential, $g^2/\boldsymbol{\lambda}$ g^2 controlled by 3rd field
spikes are ubiquitous though details change
understood via caustics of trajectory bundles: Lyapunov = strain-rate > 0
Kolmogorov-Sinai entropy (rate) = ∑positive strain-rate eigenvalues
field-strains of the deforming condensate in the ballistic regime - instability
*probability density bundles stretch s.t. - ln **ρ** = Trace strain (Shannon conserved)*
ζ(x,t) is conserved at each x in the ballistic regime
stopped by the shock in time: a burst of phonon production to alleviate the strain
ζ(x,t) is not conserved Shannon entropy S=- ln $\boldsymbol{\rho}\sqrt{G}$ = - ln **ρ** - Trace strain
spectrum of phonons is very non-thermal
slow adiabatic evolution toward thermal
phonons are the control variables for the other field degrees of freedom

⟹ subdominant nonG ubiquitous, need **χ**-light

single field V heating slow, oscillating
but shaped V can give rapid heating (roulette)
still driven by a radial instability $m^2_{eff}<0$
field-strain story the same but no modulation
⇒ transverse fields to get observable nonG



$a =$ 1

A visualized 2D slice

in lattice simulation

Preheating After

Roulette Inflation

$\langle \tau \rangle =$

quantum
diffusion
spatial jitter

drift

EoI

roulette oscillations
highly damped
$m^2_{eff}=0$ => no-non-G
if redirect by χ_{eoi}, g
let there be
heat
=> non-G??

semi ETERNAL INFLATION
EMERGENCE

EoI horizon ~ 1cm comoving

www.youtube.com/watch?v=FW__su-W-ck&NR=1

Barnaby,Bond,Huang,Kofman09

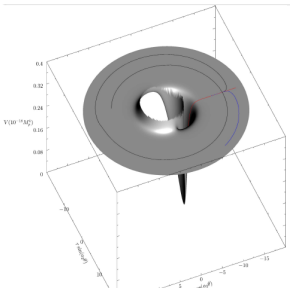
stochastic inflation:
the battle of classical drift V_c &
diffusion of quantum fluctuations V_D
$V_c \sim \nabla S_R$ $V_D = D_H \nabla S_I$
eternal inflation $\Rightarrow V_D$ dominates

emergence $\Rightarrow V_C$ dominates

inflaton+isocons potential $V(\varphi,\chi,..)$=?

$\varphi_c, \chi_c, .., \alpha_c, H_c$

$V(\varphi,\chi,..)$



Preheating After

Roulette Inflation

$\langle \tau \rangle =$

$\hbar H_c$

quantum diffusion

spatial jitter

$-M_{Pl} \nabla \ln H_c$

drift

φ

entropy generation in preheating from the coherent inflaton (origin of all matter)

isocon directions χ

e.g., axion

let there be heat

semi ETERNAL INFLATION

EMERGENCE

conformal potential-flattening eg Higgs inflation SBB89 etc

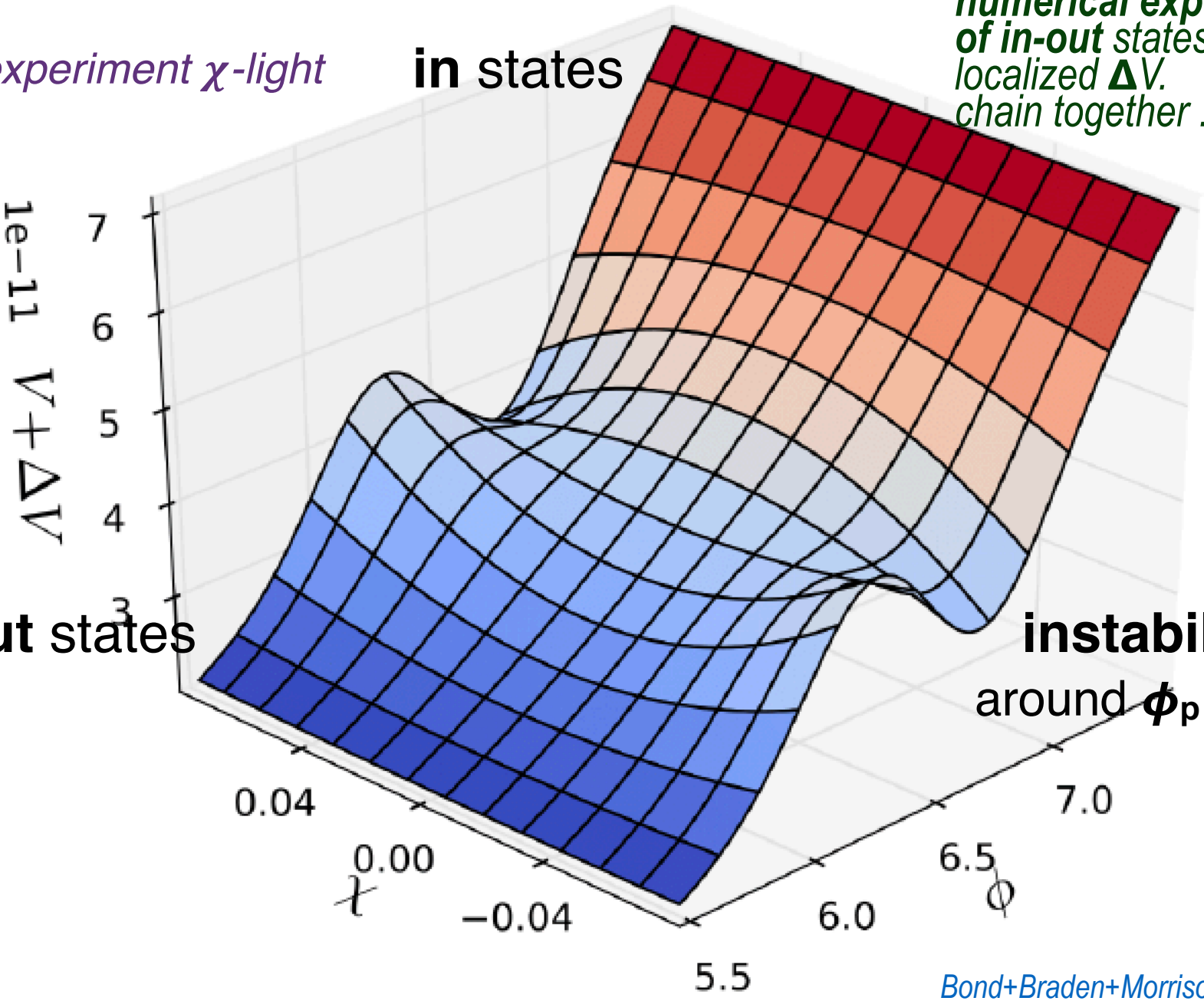
B2FH, b+braden+frolov+huang

during inflation - instabilities => entropy => nonG

experiment χ-light

in states

***numerical experiments of in-out** states through localized ΔV. chain together .. oscillating*

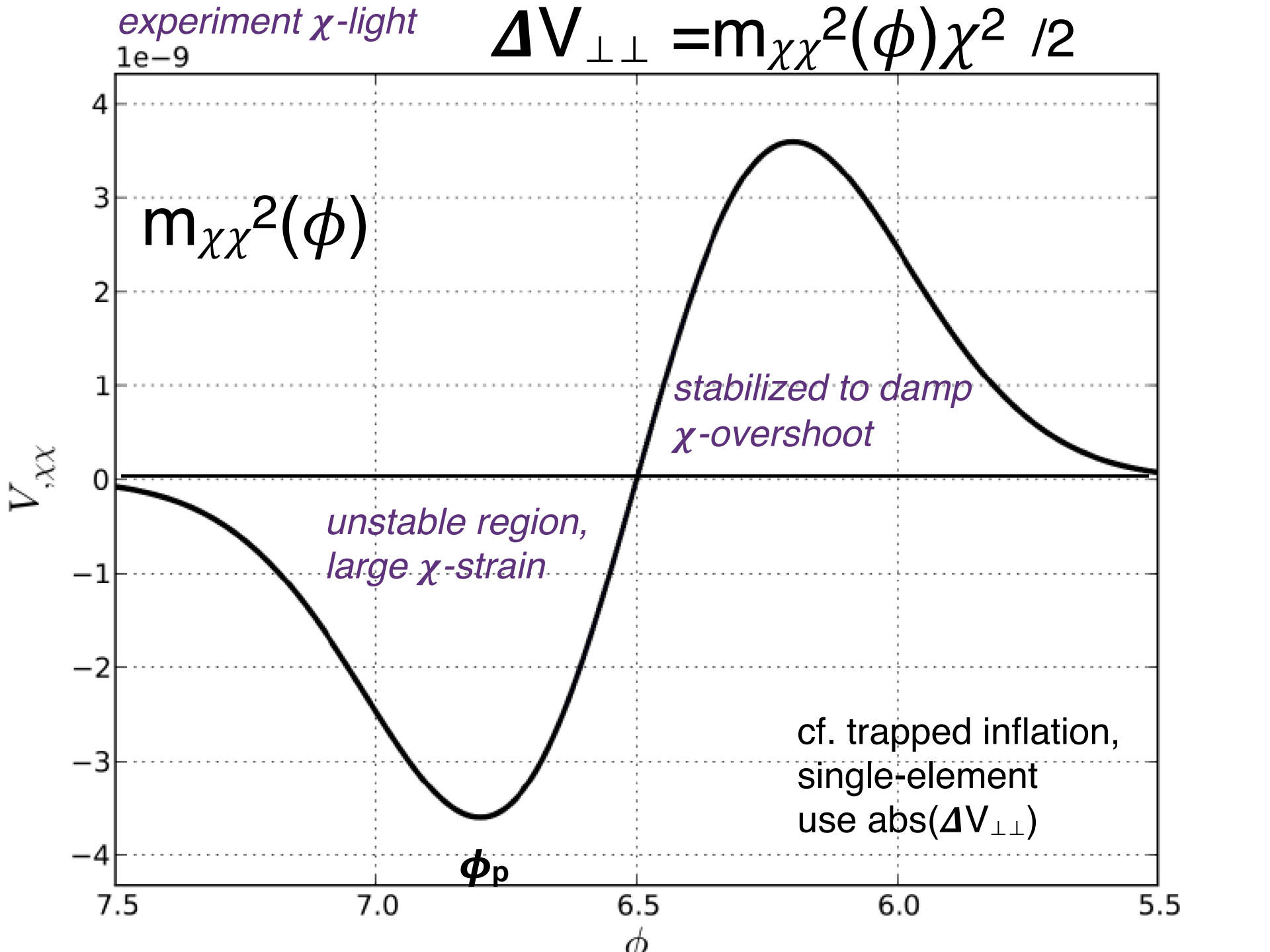


out states

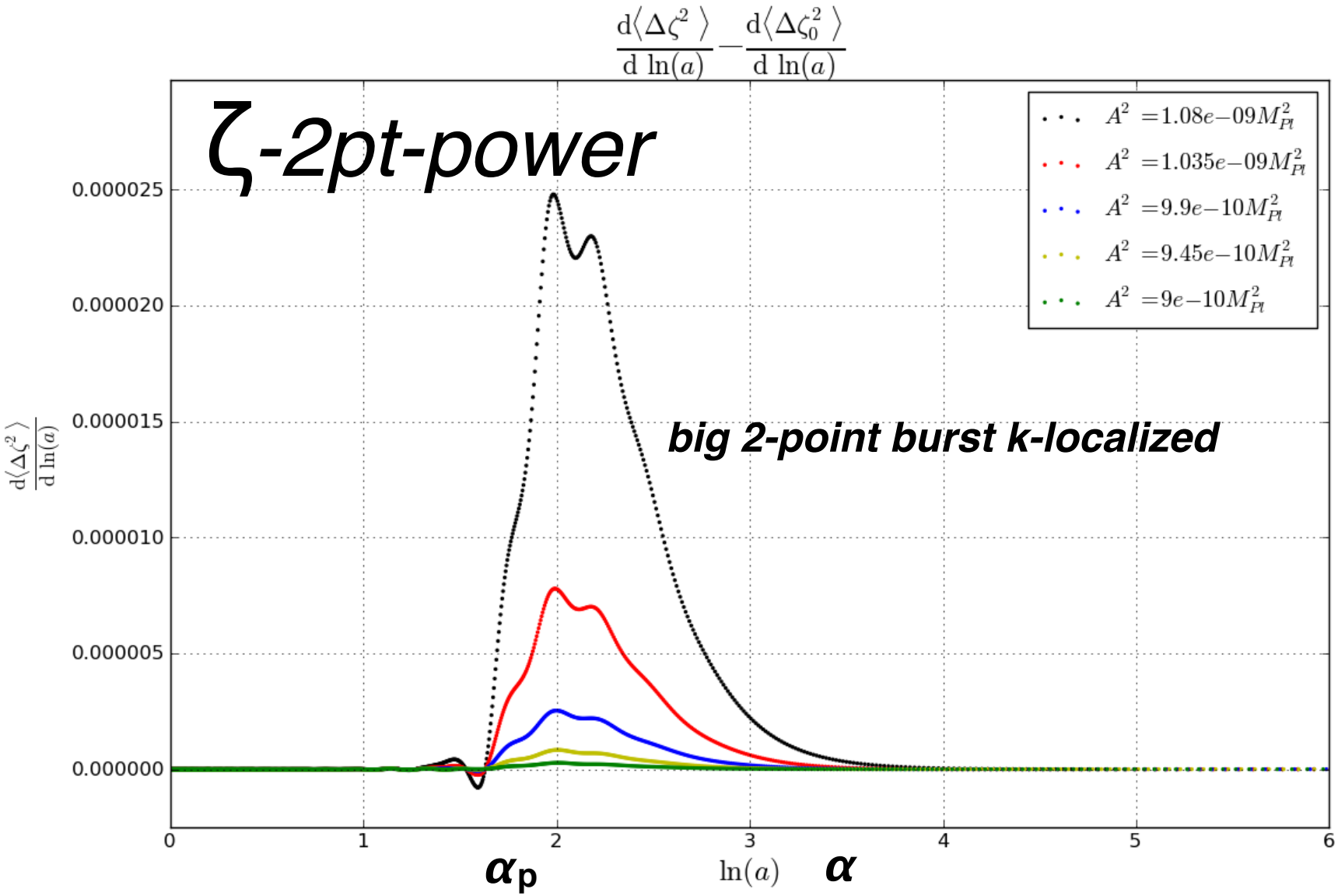
instability

around ϕ_p k_p α_p

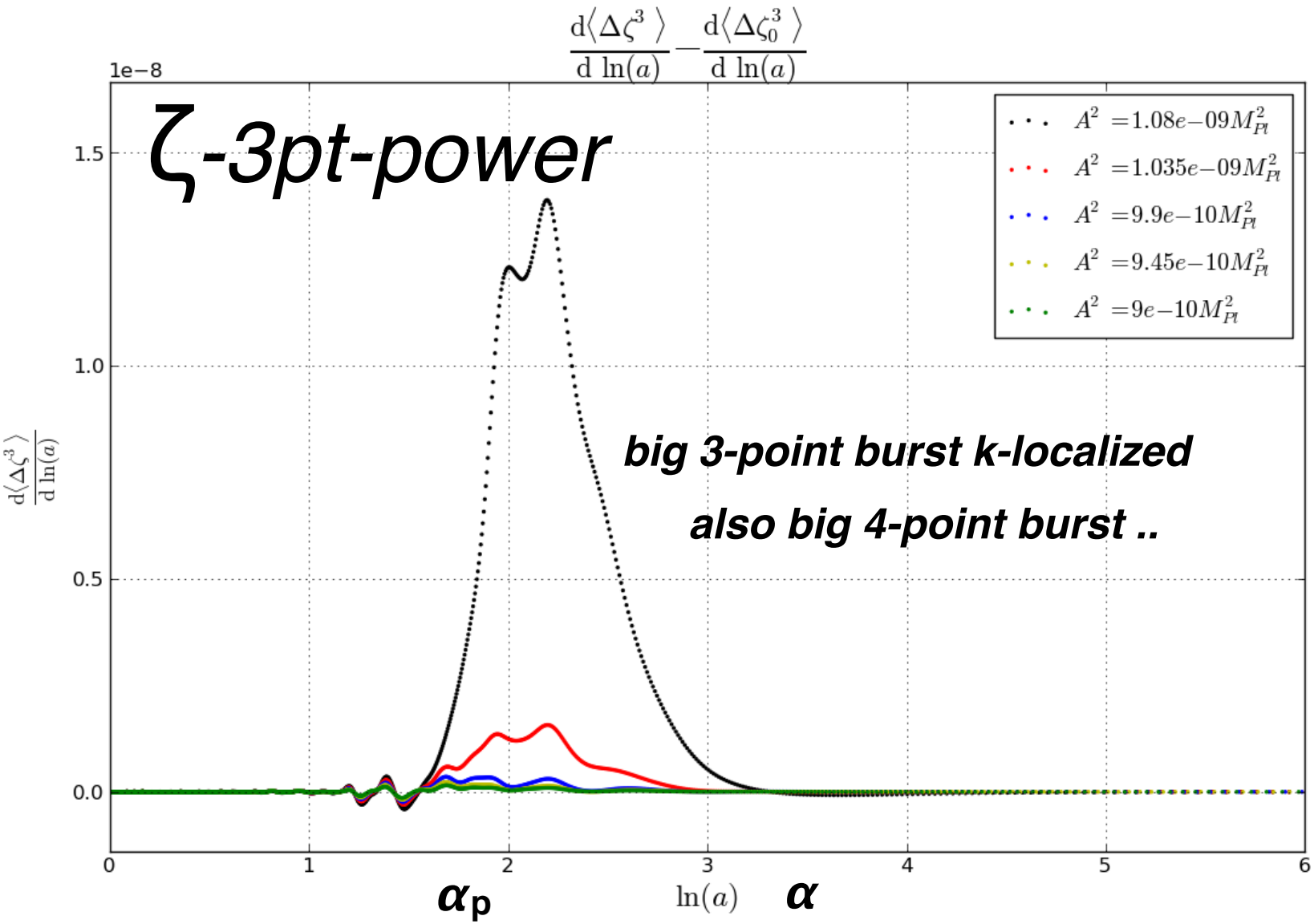
Bond+Braden+Morrison


experiment χ-light
$\Delta V_{\perp\perp} = m_{\chi\chi}^2(\phi)\chi^2/2$
1e−9
$m_{\chi\chi}^2(\phi)$
stabilized to damp
χ-overshoot
unstable region,
large χ-strain
cf. trapped inflation,
single-element
use abs($\Delta V_{\perp\perp}$)
ϕ_p
$V_{,\chi\chi}$
ϕ
4
3
2
1
0
−1
−2
−3
−4
7.5
7.0
6.5
6.0
5.5

experiment χ-light



experiment χ-light

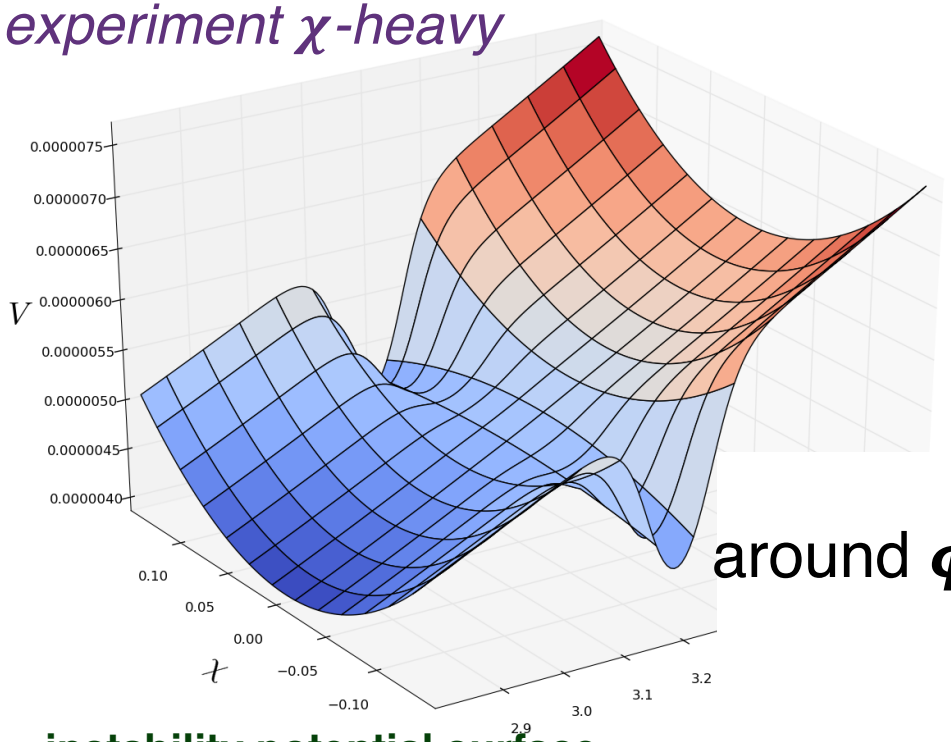


TBD coherence of N-point bursts in N-space ..

during inflation - instabilities => entropy => nonG

experiment χ-heavy

***numerical experiments of in-out** states through localized **Δ**V. chain together .. oscillating*

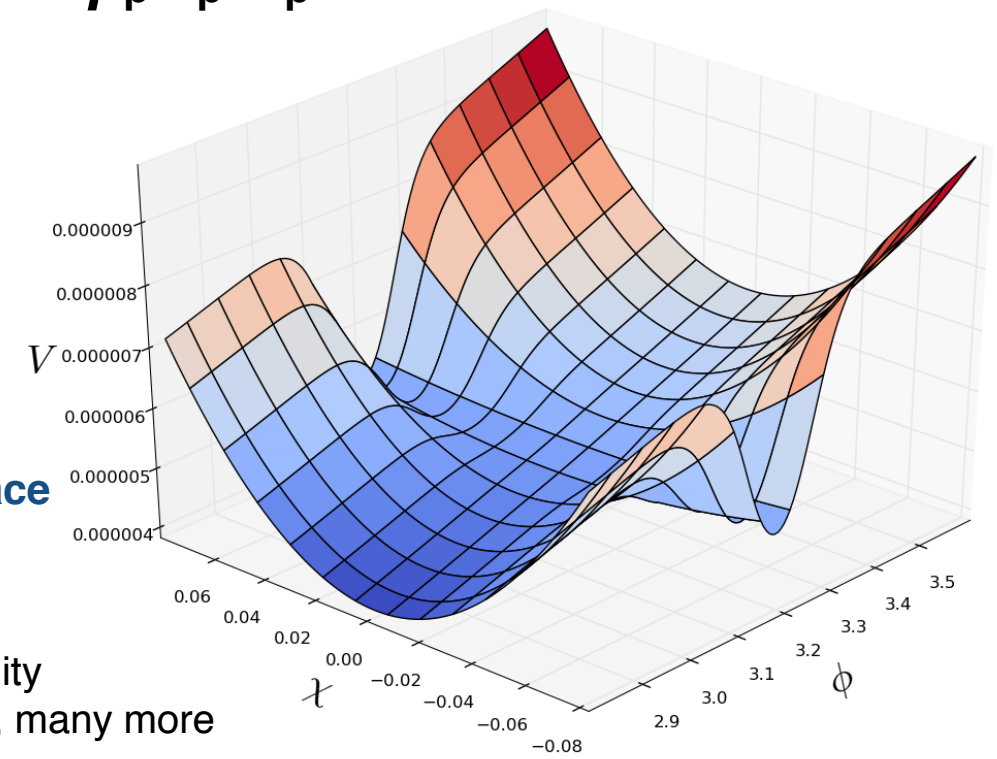


around ϕ_p k_p α_p

instability potential surface

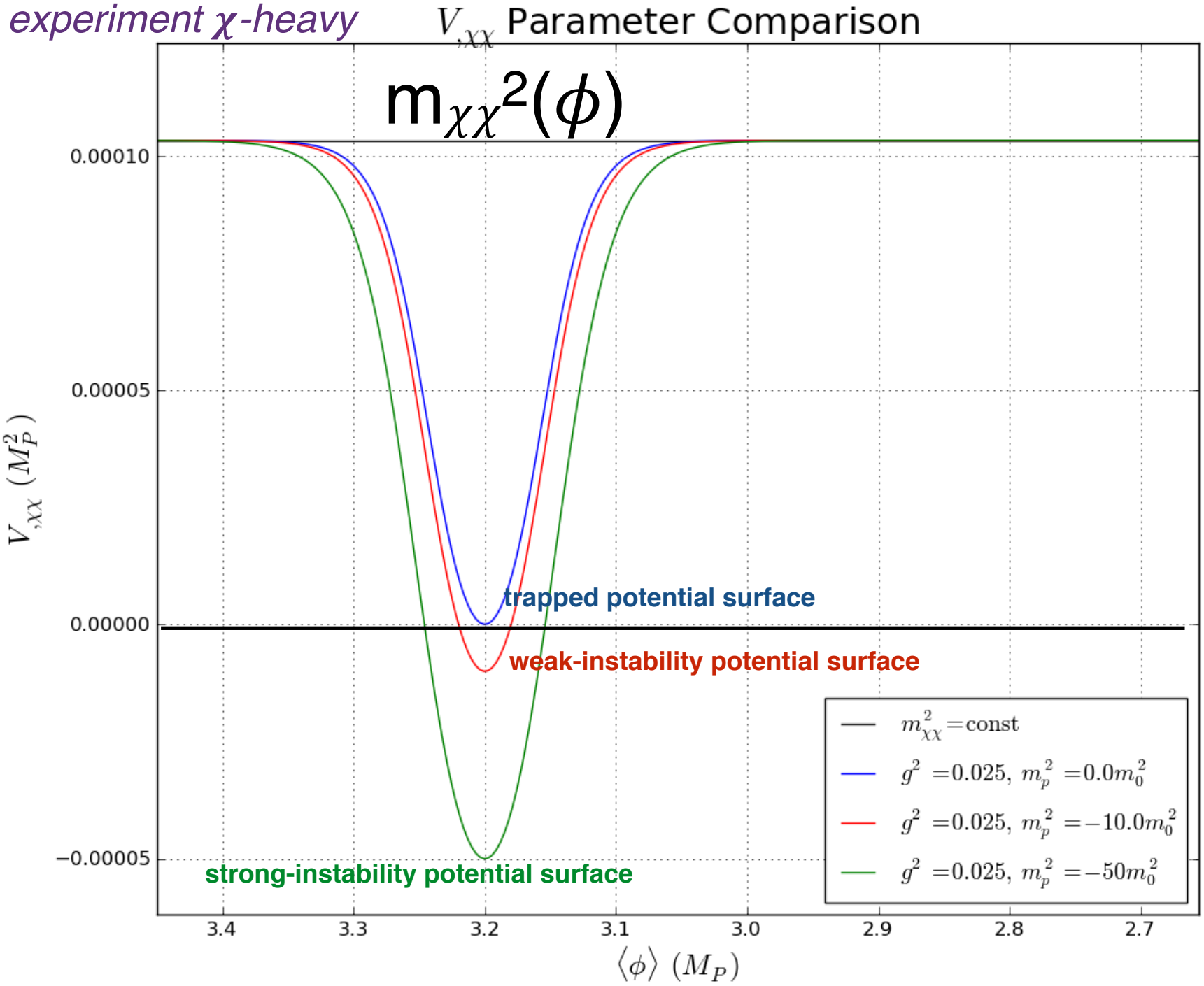
Bond+Braden+Frolov+Morrison

trapped potential surface

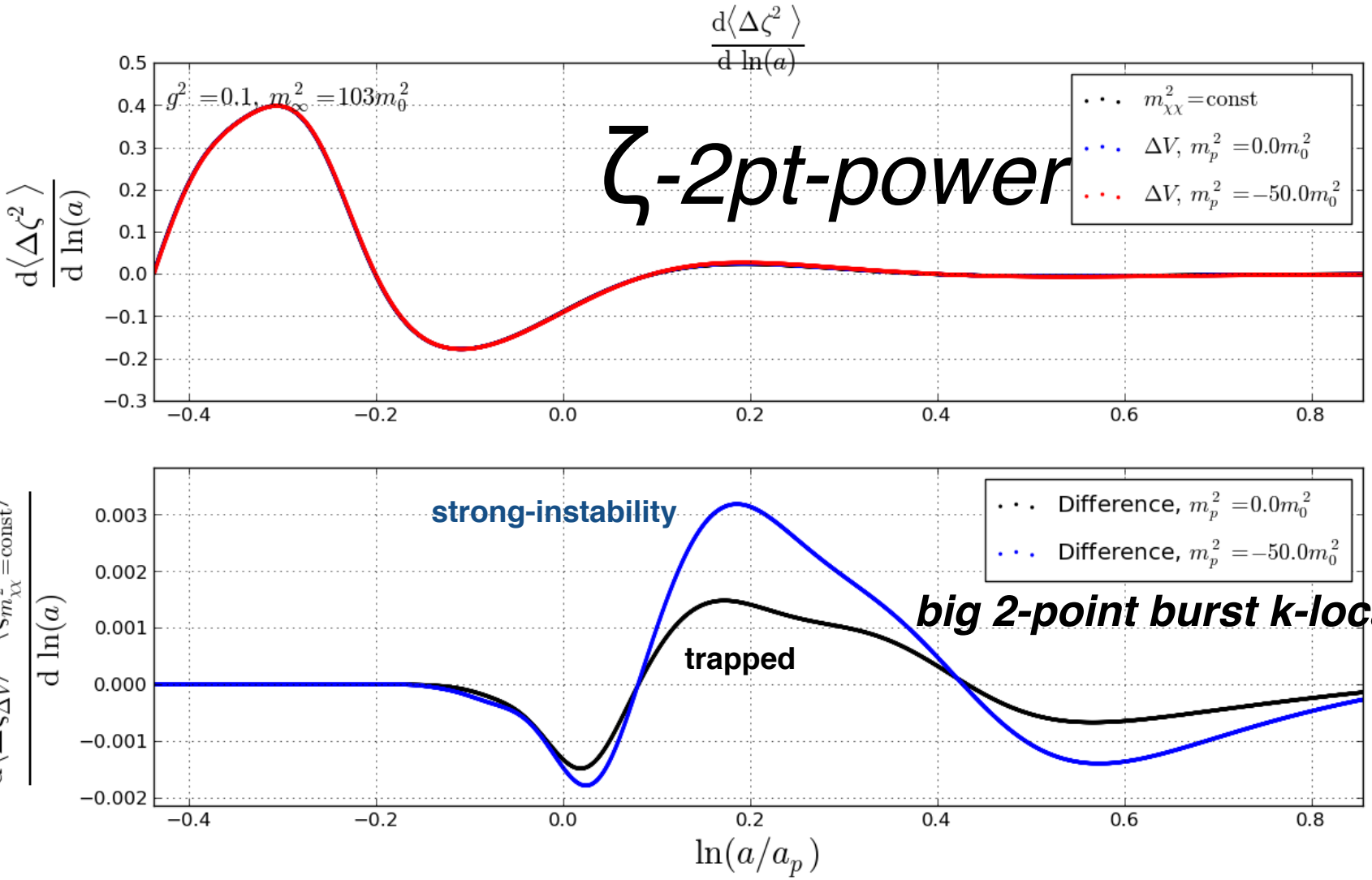


trapped inflation: *same parameters,* no instability
.. Kofman, Silverstein, Green, Barnaby, Huang, many more

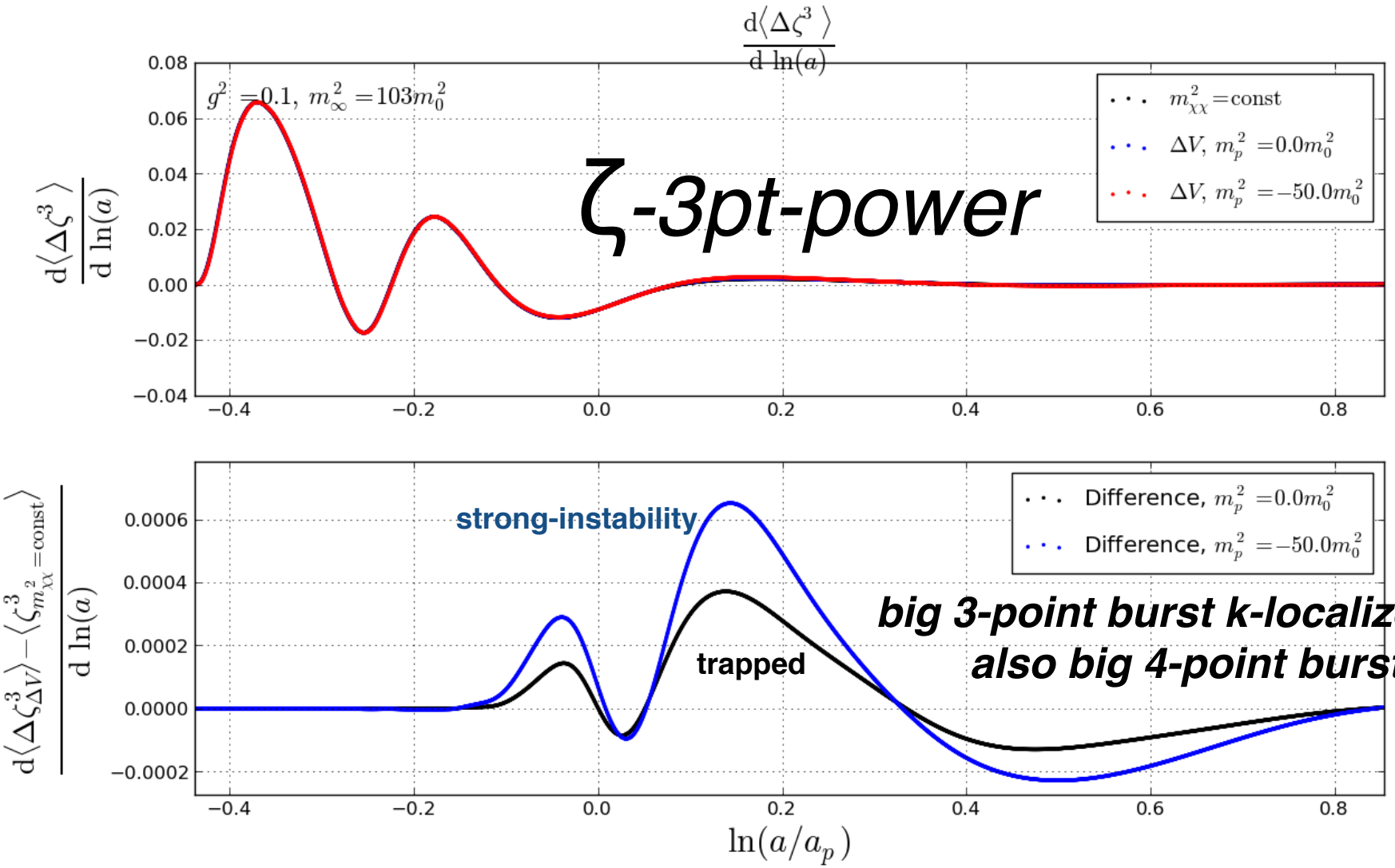
experiment χ-heavy



experiment χ-heavy *unstable χ cf. trapped*

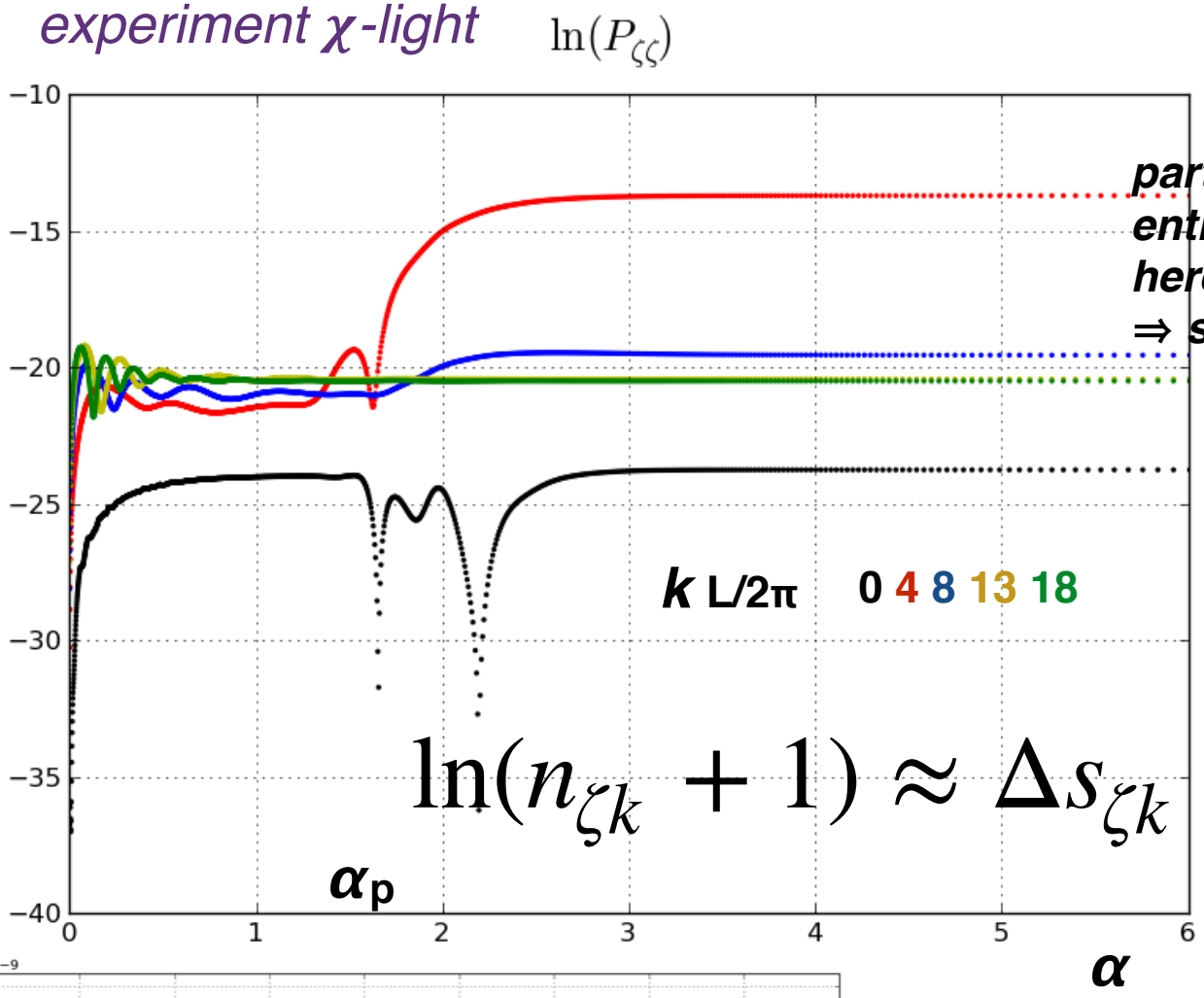


experiment χ-heavy *unstable χ cf. trapped*



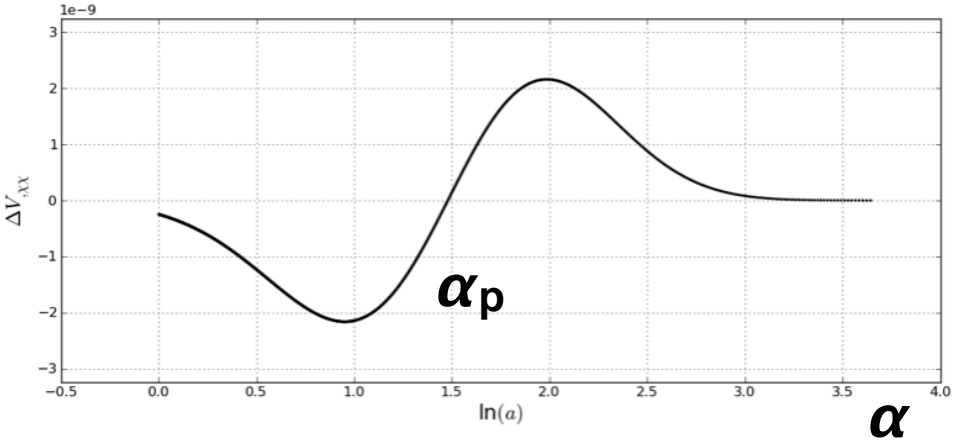
TBD coherence of N-point bursts in N-space ..

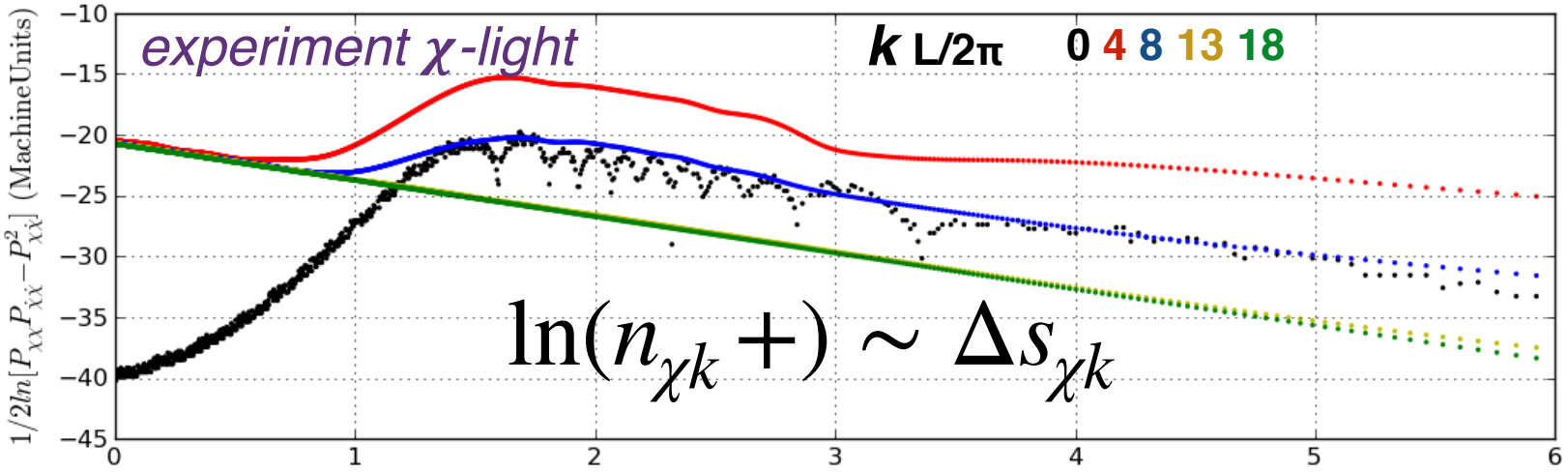
experiment χ-light

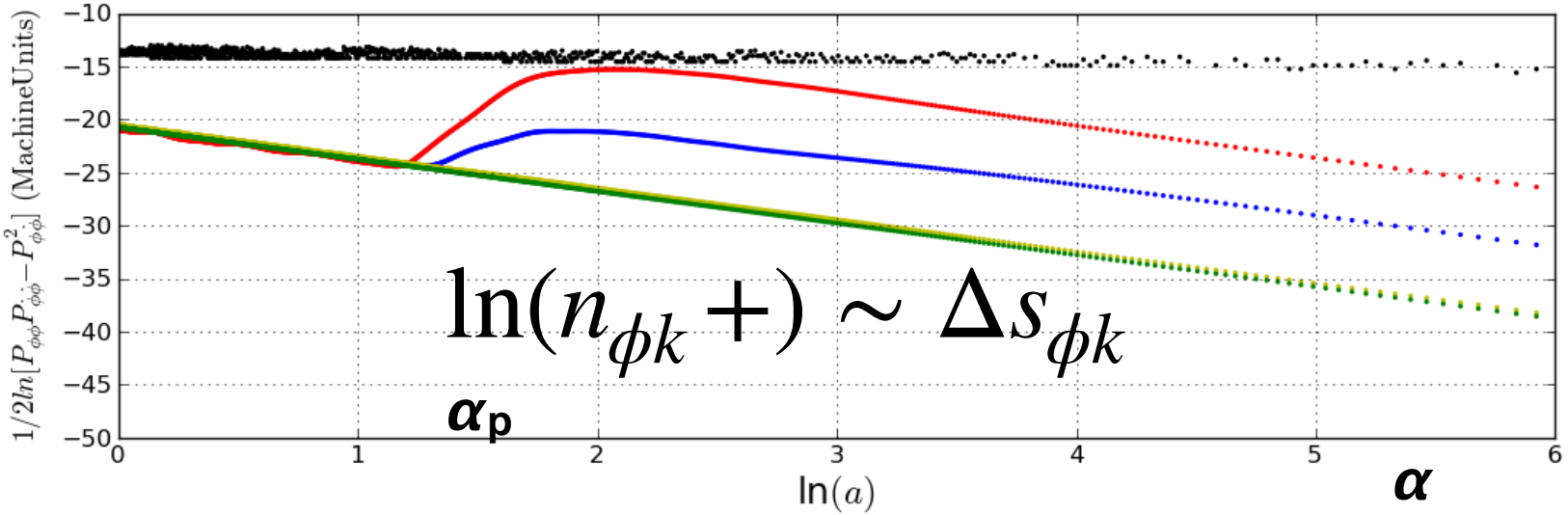


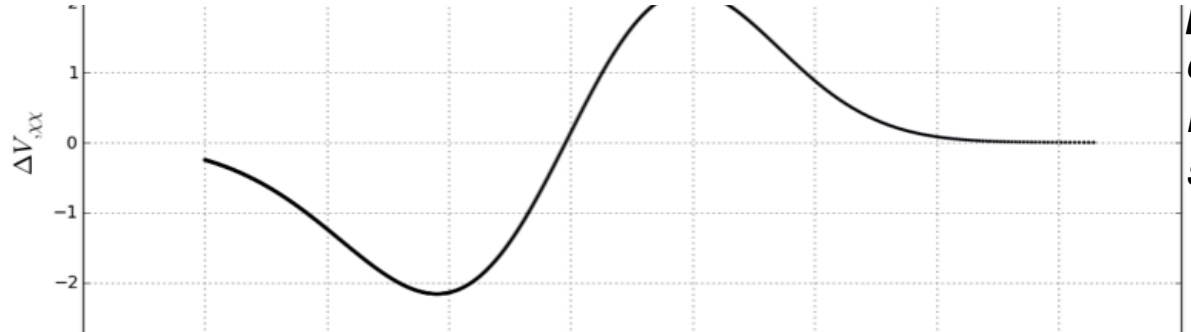
particle production picture *aka*
entropy production picture
here shown in phonons
⇒ soft rather than hard

phonon occupation



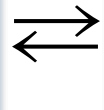






particle production picture *aka*
entropy production picture
here in isocons χ & inflatons ϕ
soft particle production

Novel LSS/CMB non-Gaussianities from Instabilities & Entropy Generation During and After Inflation



Generate fully-correlated nonGaussian Websky-Ensembles for CMB/LSS probes

Dick Bond @ PSU 19 02 01

what are the degrees of freedom / parameters of the ultra early Universe? TBD

begin-inflate => inflate => end-inflate => preheat => non-equilibrium heat+entropy
=> *Standard Model particle physics* QG plasma radiation dominated
=> dark matter dominated *structure via gravitational instability* => dark energy now

$$d\zeta(x,t) = (dE+pdV)/3(E+pV) = d\, ln\rho_c / 3(1+w_c) + \text{Trace}\, d\alpha^i{}_j$$

***fit into** a UV-complete theory (ultra-high energy to the Planck scale) strings, landscape, ..*
& IR-complete theory (post-inflation heating -> quark/gluon plasma)??? TBD

*role of (1) **instabilities after inflation***
entropy generation via the breakup of the deforming coherent low-k inflaton condensate into incoherent high-k fluctuations aka phonons at a "shock-in-time" ⇒ **nonGaussianity**

*role of (2) **instabilities during inflation***
phenomenology of in-states propagating through localized unstable potential structures to out-states, like scattering theory ⇒ *k-localized* **nonGaussianity**

*(3) **|cg <=> fg> condensate/fluctuation framework**, for both using coherent states classical-like approach with $\hbar$.*

*includes **Bogoliubov** transformations for fluctuations as condensate evolves => **particle creation** interpretation in both heating and inflating regimes.*

END